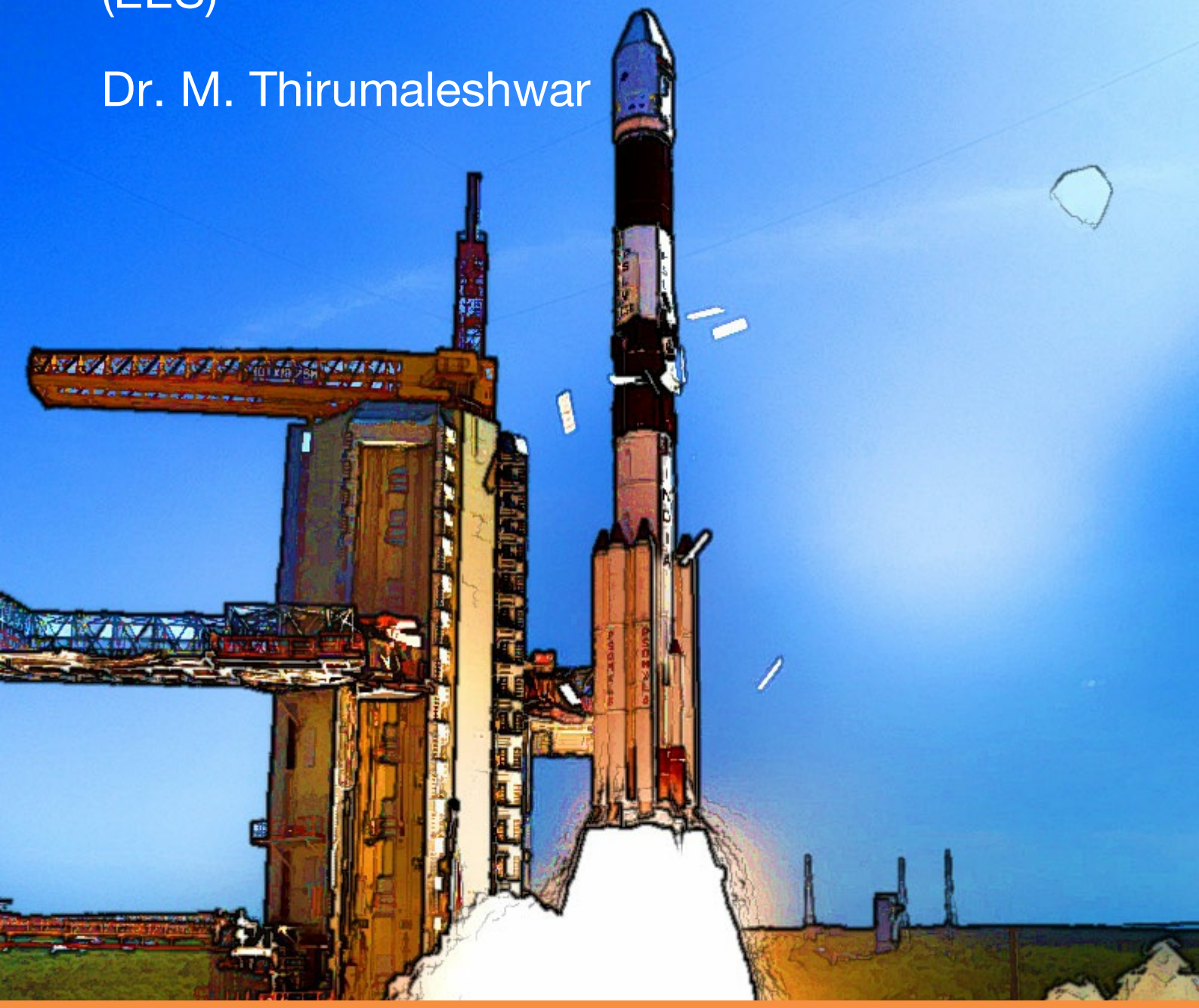
Cryog. Engineering: Software Solutions Part-III-B

Cryogenic Refrigeration systems: Problems (EES)

Dr. M. Thirumaleshwar



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CRYOGENIC ENGINEERING: SOFTWARE SOLUTIONS PART-III-B

CRYOGENIC REFRIGERATION SYSTEMS – PROBLEMS (EES)

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Cryogenic Engineering: Software Solutions Part-III-B: Cryogenic Refrigeration systems – Problems (EES)
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Cryogenic Engineering: Software Solutions Part-III-B: Cryogenic Refrigeration systems – Problems (EES)

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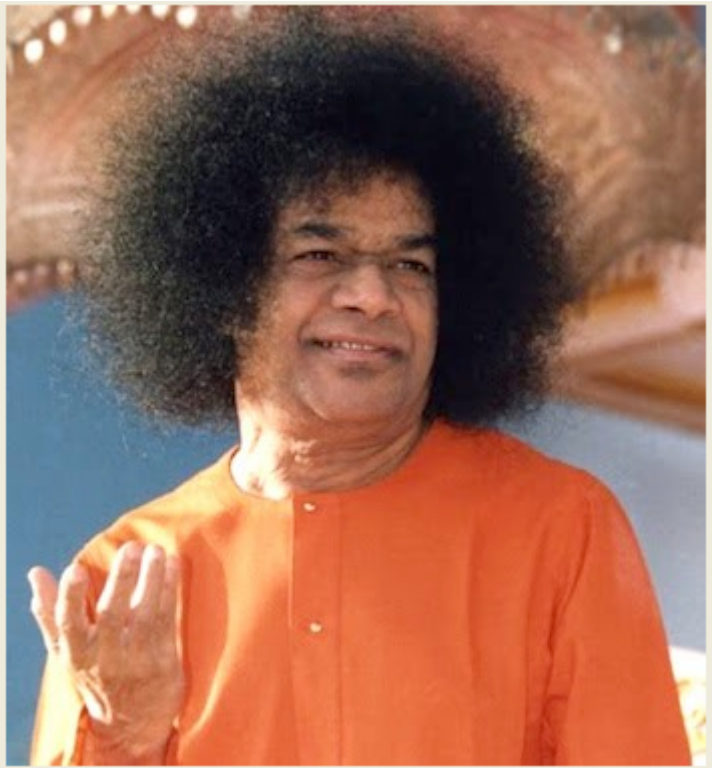
DEDICATION

This work is lovingly dedicated at the lotus feet of

Bhagavan Sri Sathya Sai Baba



"There is only one religion, the religion of Love.
There is only one caste, the caste of Humanity.
There is only one language, the language of the Heart.
There is only one God, He is Omnipresent."

"Help Ever, Hurt Never!"

…Bhagavan Sri Sathya Sai Baba

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PREFACE

This book, viz. **Cryogenic Engineering: Software solutions – Part-III-B**, is the third volume in the series on **Cryogenic Engineering: Software Solutions**.

This part is being published in two volumes, viz. Cryogenic Engineering: Software solutions – Part-III A and Part-III B. Part-III A contains a brief summary of background theory, definitions and formulas and the problems solved with Mathcad. Part-III B contains problems solved with Engineering Equation Solver (EES). ***So, it is advisable that one refers to both the parts.***

As with the Part-I and II of the series, focus here is on the solutions of problems in cryogenic engineering using software such as Mathcad and Engineering Equation Solver (EES). *Only the essential theory and summary of equations required for calculations are given at the beginning of the chapter*.

Advantages of using computer software to solve problems are reiterated:

i) It helps in solving the problems fast and accurately
ii) Parametric analysis (what-if analysis) and graphical visualization is done very easily. This helps in an in-depth analysis of the problem.
iii) Once a particular type of problem is solved, it can be used as a *template* and solving similar problems later becomes extremely easy.
iv) In addition, one can plot the data, curve fit, write functions for various properties or calculations and re-use them.
v) These possibilities create interest, curiosity and wonder in the minds of students and enthuse them to know more and work more.

This book, viz. **Cryogenic Engineering: Software solutions – Part-III-B** deals with the **Cryogenic refrigeration systems. Here, based on the theory and equations summarized in Part-III-A, many Functions and Procedures are written using Engineering Equation Solver (EES) and problems are solved to illustrate the use of these Functions/Procedures.**

EES has a great advantage that it has in-built Functions for properties of most of the cryogenic fluids and materials required for our calculations. Thus, it is very convenient to use EES.

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In Part-III A of this book, theoretical background and summary of calculation equations are given on various topics under **Cryogenic refrigeration systems. Topics covered are:**

Thermodynamically ideal isothermal source system, concept of Coeff. of Performance (COP) and Figure of Merit (FOM), thermodynamically ideal isobaric source system, simple Linde-Hampson (L-H) refrigerator, pre-cooled L-H system, Claude refrigeration system, cold gas refrigeration system, Philips (or Stirling cycle) refrigerator, Vuilleumier cycle refrigerator, Solvay cycle and Gifford-McMahon (GM) cycle refrigerators etc., Magnetic cooling, i.e. Adiabatic demagnetization of paramagnetic materials, calculation of magnetic moments and entropy of paramagnetic materials, He^3-He^4 Dilution refrigerator, and Nuclear adiabatic demagnetization. Importance of regenerators used in Philips and GM cycle refrigerators and the design equations are summarized. Several Functions are written in Mathcad to simplify the standard and most required calculations. Students, teachers, researchers and professionals may find them very useful.

S.I. Units are used throughout this book. Wide variety of worked examples presented in the book should be useful for those appearing for University, AMIE and Engineering Services examinations.

Acknowledgements: Firstly, I would like to **thank all my students**, who have been an inspiration to me in all my academic efforts.

Sincere thanks are due to **Rev. Fr. Joseph Lobo**, Director, St. Joseph Engineering College, Mangalore, for his kindness, regard and words of encouragement.

I am also thankful to **Dr. Thirumaleshwara Bhat**, Principal, Sri Madhwa Vadiraja Institute of Technology and Management, Bantakal, Udupi, for giving me support in my academic activities.

I gratefully remember my former colleagues at the Cryogenics section of Technical Physics Division, Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology, Indore for their sincere cooperation in a true spirit of team-work in all the projects that we undertook.

I particularly salute and admire the vision and foresight of former Heads of Technical Physics Division, BARC viz. late Mr. C. Ambasankaran, Mr. R.Y. Deshpande, Dr. S.R. Gowariker and late Mr. S.S. Ramamurthy in initiating and guiding many of the 'first of its kind' projects for Indian Space Research Organization (ISRO), wherein the Cryogenics section was deeply involved in the design and execution of the projects.

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I am especially grateful to Prof. R.G. Scurlock, former Director of Institute of Cryogenics, University of Southampton, (U.K.) for writing a message for the Part-I of this series.

It was indeed gracious of my former Professor, under whom I studied for M.Sc. in Cryogenics at the University of Southampton, U.K. during 1970–72, and worked as a Visiting Research Fellow during 1993–94, to honor me by writing this message.

My special thanks to **Bookboon.com** for publishing this *free ebook*. **Ms Karin Jakobsen** and the editorial staff have been most patient and helpful.

Finally, I would like to express my sincere thanks and appreciation to my **wife, Kala,** who, as usual, has given me continuous support, help and encouragement in all my academic activities, making many silent sacrifices.

M. Thirumaleshwar
January, 2017
Email: tmuliya@rediffmail.com

Note: Along with this book, two zip files are also available for free download. They contain several 'stand alone' .exe files to calculate performance parameters of many Cryogenics liquefiers and refrigerators. They should be of great use for students, teachers and researches for quick verification of their calculations.

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ABOUT THE AUTHOR

Dr. M. Thirumaleshwar graduated in Mechanical Engineering from Karnataka Regional Engineering College, Surathkal, Karnataka, India, in the year 1965. He obtained M.Sc (cryogenics) from University of Southampton, U.K. and Ph.D (cryogenics) from Indian Institute of Science, Bangalore, India.

He is a Fellow of Institution of Engineers (India), Life Member, Indian Society for Technical Education, and a Foundation Fellow of Indian Cryogenics Council.

He has worked in India and abroad on large projects in the areas involving heat transfer, fluid flow, vacuum system design, cryo-pumping etc.

He worked as Head of Cryogenics Dept. in Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology (CAT), Indore, from 1966 to 1992.

He worked as Guest Collaborator with Superconducting Super Collider Laboratory of Universities Research Association, in Dallas, USA from 1990 to 1993.

He also worked at the Institute of Cryogenics, Southampton, U.K. as a Visiting Research Fellow from 1993 to 1994.

He was Head of the Dept. of Mechanical Engineering, Fr. Conceicao Rodrigues Institute of Technology, Vashi, Navi Mumbai, India for eight years.

He also worked as Head of Dept. of Mechanical Engineering and Civil Engineering, and then as Principal, Vivekananda College of Engineering and Technology, Puttur (D.K.), India.

He was Professor and coordinator of Post-graduate program in the Dept. of Mechanical Engineering in St. Joseph Engineering College, Vamanjoor, Mangalore, India.

A book entitled **"Fundamentals of Heat and Mass Transfer"** authored by him and published by M/s Pearson Education, India (2006) **has been adopted as a Text book** for third year engineering students by the Visweswaraya Technological University (V.T.U.), Belgaum, India.

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He has authored a *free e-book* entitled **"Software Solutions to Problems on Heat Transfer"** wherein problems are solved using 4 software viz. Mathcad, EES, FEHT and EXCEL. This book, containing about 2750 pages, is presented in 9 parts and all the 9 parts can be downloaded *for free* from www.bookboon.com

He has also authored ***free e-books*** **on Thermodynamics** entitled **"Basic Thermodynamics: Software Solutions" and "Applied Thermodynamics: Software Solutions"** wherein problems are solved using 3 software viz. Mathcad, EES, and TEST. Each of these titles is presented in 5 parts and all the books can be downloaded *for free* from www.bookboon.com

In addition, he has authored following two useful *free ebooks*:

i) Applied Thermodynamics: Software Solutions: Vapor compression Refrigeration cycle + Problems (Mathcad)

http://bookboon.com/en/applied-thermodynamics-software-solutions-vapor-ebook

ii) Applied Thermodynamics: Software Solutions: Vapor Power cycles (Rankine cycle) + Problems (Mathcad)

http://bookboon.com/en/applied-thermodynamics-software-solutions-vapor-po-ebook

His earlier *free ebooks in this* **Cryogenic Engineering series**, viz. **Cryogenic Engineering: Software Solutions – Parts-I, II-A and II-B** were published by Bookboon about an year ago.

He has also authored **three motivational, free ebooks**, published by www.bookboon.com, entitled as follows:

1. Towards Excellence… How to Study (A Guide book to Students)
2. Towards Excellence… How to teach (A guide book to Teachers)
3. Towards Excellence… Seminars, GD's and Personal Interviews

Dr. M. Thirumaleshwar has attended several National and International conferences and has more than 50 publications to his credit.

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ABOUT THE SOFTWARE USED

Following three software are used while solving problems in this book series:

1. Mathcad 7 and Mathcad 15 (Ref: www.ptc.com)
2. Engineering Equation Solver (EES) (Ref: www.fchart.com), and

For a brief introduction to Mathcad, EES and EXCEL see the chapter 1 of the following *free ebook* by the author:

"Software Solutions to Problems on Heat Transfer – CONDUCTION-Part-I":
http://bookboon.com/en/software-solutions-to-problems-on-heat-transfer-ebook

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4 CRYOGENIC REFRIGERATION SYSTEMS: PROBLEMS (EES)

Learning objectives:

1. In this chapter, topics on 'cryogenic refrigeration systems' are dealt with.
2. Part-III-A gave theoretical background and summary of calculation equations on various topics: thermodynamically ideal isothermal source system, Coeff. of Performance (COP), Figure of Merit (FOM), thermodynamically ideal isobaric source system, simple Linde-Hampson (L-H) refrigerator, pre-cooled L-H system, Claude refrigeration system, cold gas refrigeration system, Philips (or Stirling cycle) refrigerator, Vuilleumier cycle refrigerator, Solvay cycle and Gifford-McMahon (GM) cycle refrigerators, Magnetic cooling, i.e. Adiabatic demagnetization of paramagnetic materials, calculation of magnetic moments and entropy of paramagnetic materials, He^3-He^4 Dilution refrigerator, and Nuclear adiabatic demagnetization. Many numerical problems are solved to illustrate the ease of computer calculations using Mathcad software.
3. Here, in Part-III-B, we write many Functions and Procedures in Engineering Equation Solver (EES) to simplify the calculations.
4. Several problems are worked out to illustrate the use of these EES Functions/ Procedures.

4.1 DEFINITIONS, STATEMENTS AND FORMULAS USED[1–9]: SEE PART-III-A

4.2 PROBLEMS SOLVED WITH MATHCAD: SEE PART-III-A

4.3 PROBLEMS SOLVED WITH EES

"**Prob. 4.3.1** Write an EES Procedure to calculate the COP and Work requirement for a Thermodynamically Ideal, Isothermal source system.[1]. And, plot the COP against various source temps. Tc for a constant sink temp. Th = 300 K."

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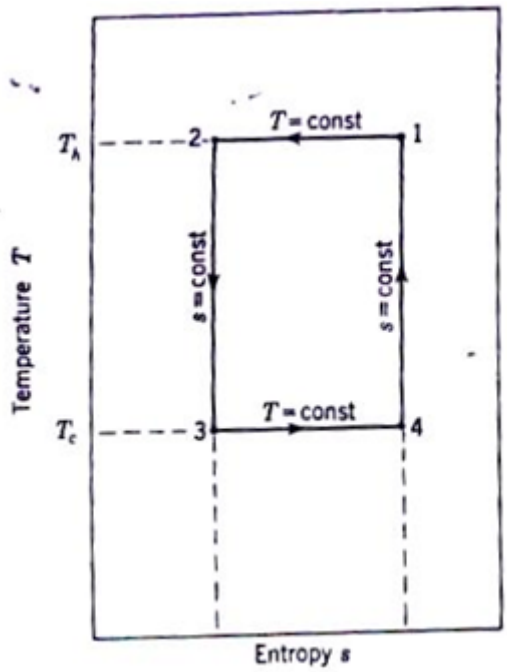

First, write the EES Procedure:

PROCEDURE Ideal_isoth(Tc, Th:COP_i, WbyQ)

"Inputs: Tc, Th … cold and hot temps, Temp in K"

"Outputs: COP_i, WbyQ (kJ/kJ)"

COP_i:=Tc / (Th – Tc)

WbyQ:= 1 / COP_i "[kJ/kg]"

END

"=========="

Now, use this Procedure to do calculations required:

"Ex:"

Tc = 77 "K"

Th = 300 "K"

CALL Ideal_isoth(Tc, Th:COP_i, WbyQ)

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Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP_i = 0.3453 Tc = 77 [K] Th = 300 [K] WbyQ = 2.896 [kJ/kJ]

To plot COP vs Tc:

First, produce the Parametric Table:

1..8	1 Tc [K]	2 Th [K]	3 COP_i	4 WbyQ [kJ/kJ]
Run 1	0.001	300	0.000003333	299999
Run 2	0.056	300	0.0001867	5356
Run 3	0.01	300	0.00003333	29999
Run 4	1	300	0.003344	299
Run 5	4.2	300	0.0142	70.43
Run 6	20.4	300	0.07296	13.71
Run 7	77.4	300	0.3477	2.876
Run 8	112	300	0.5957	1.679

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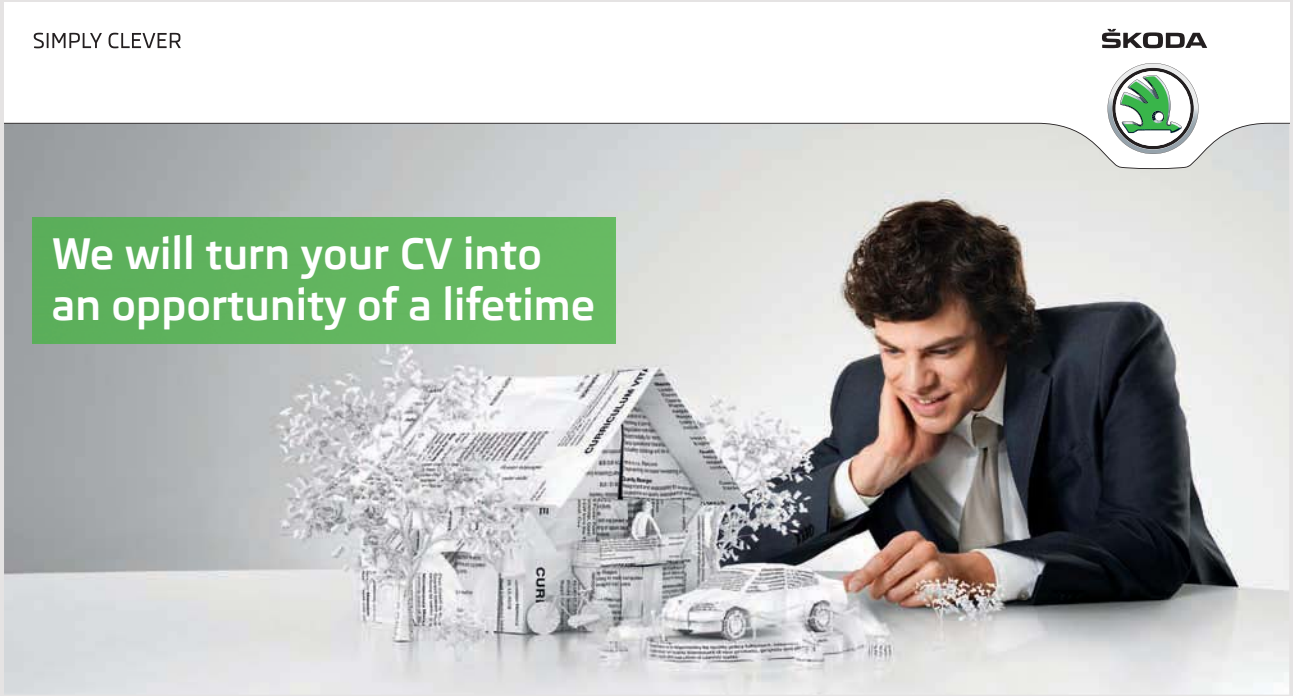

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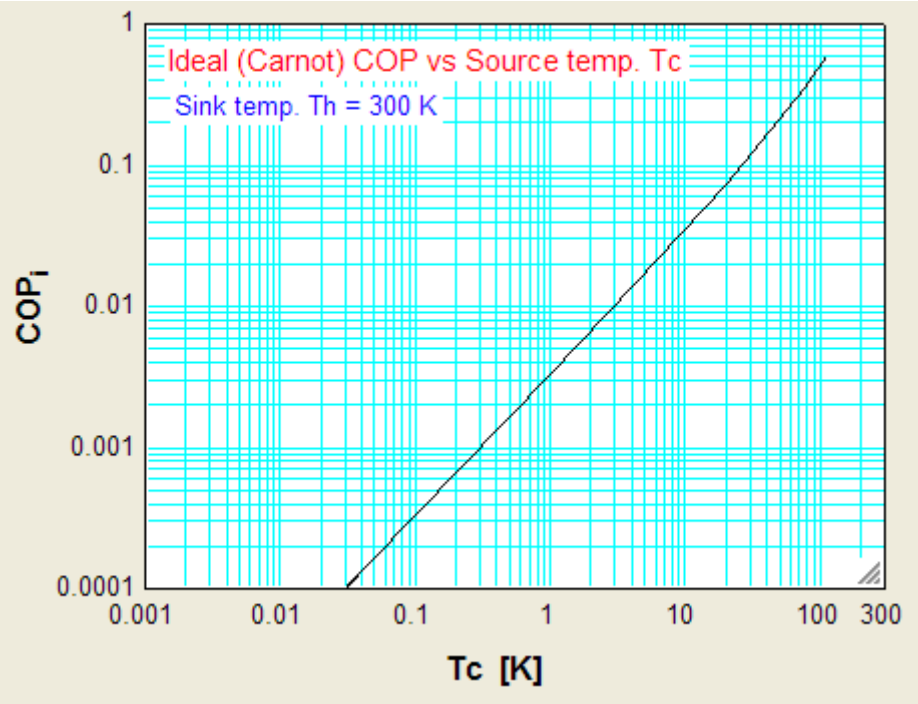
Now, plot the results:



Prob. 4.3.2 Determine the minimum work required to remove 200 W from a region at 20.4 K if the sink temp is: (a) 300 K (b) 77 K. [1]

EES Solution:

```
Q = 200 "W… at 20.4 K"

Tc = 20.4 [K]

Th1 = 300 [K]

Th2 = 77 [K]

"W1 = Min. work when Th = 300 K:"

CALL Ideal_issoth(Tc, Th1:COP_i_1, W1byQ)

W1 = W1byQ * Q "W … Min. work reqd when Th = 300 K"

"W2 = Work when Th = 77 K:"
```

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CALL Ideal_issoth(Tc, Th2:COP_i_2, W2byQ)

W2 = W2byQ * Q "W … Min. work reqd when Th = 77 K"

"=="

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

$COP_{i,1}$ = 0.07296	$COP_{i,2}$ = 0.3604	Q = 200 [W]	Tc = 20.4 [K]
Th1 = 300 [K]	Th2 = 77 [K]	W1 = 2741 [W]	W1byQ = 13.71
W2 = 554.9 [W]	W2byQ = 2.775		

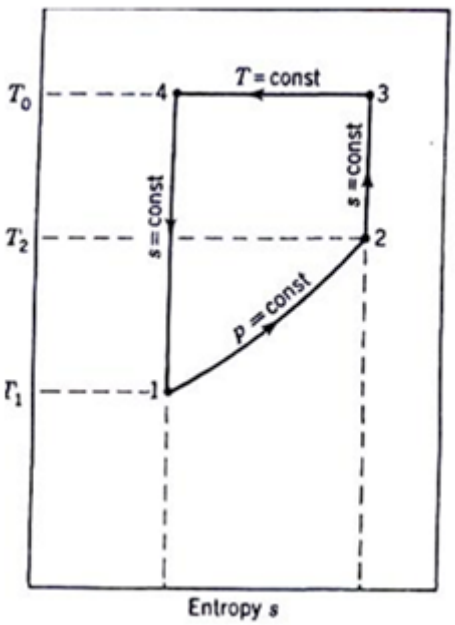
Thus:

Minimum work required to remove 200 W from a region at 20.4 K:

When Th = 300 K: W1 = 2741 W … Ans.

When Th = 77 K: W2 = 554.9 W … Ans.

Prob. 4.3.3 Write an EES Procedure to calculate COP and WbyQ for a Thermodynamically Ideal, Isobaric source system, for an ideal gas. Then, find COP and WbyQ when source temp is from T1 = 112 K to T2 = 190 K, and sink temp T0 = 300 K. Plot COP vs T1by T0.



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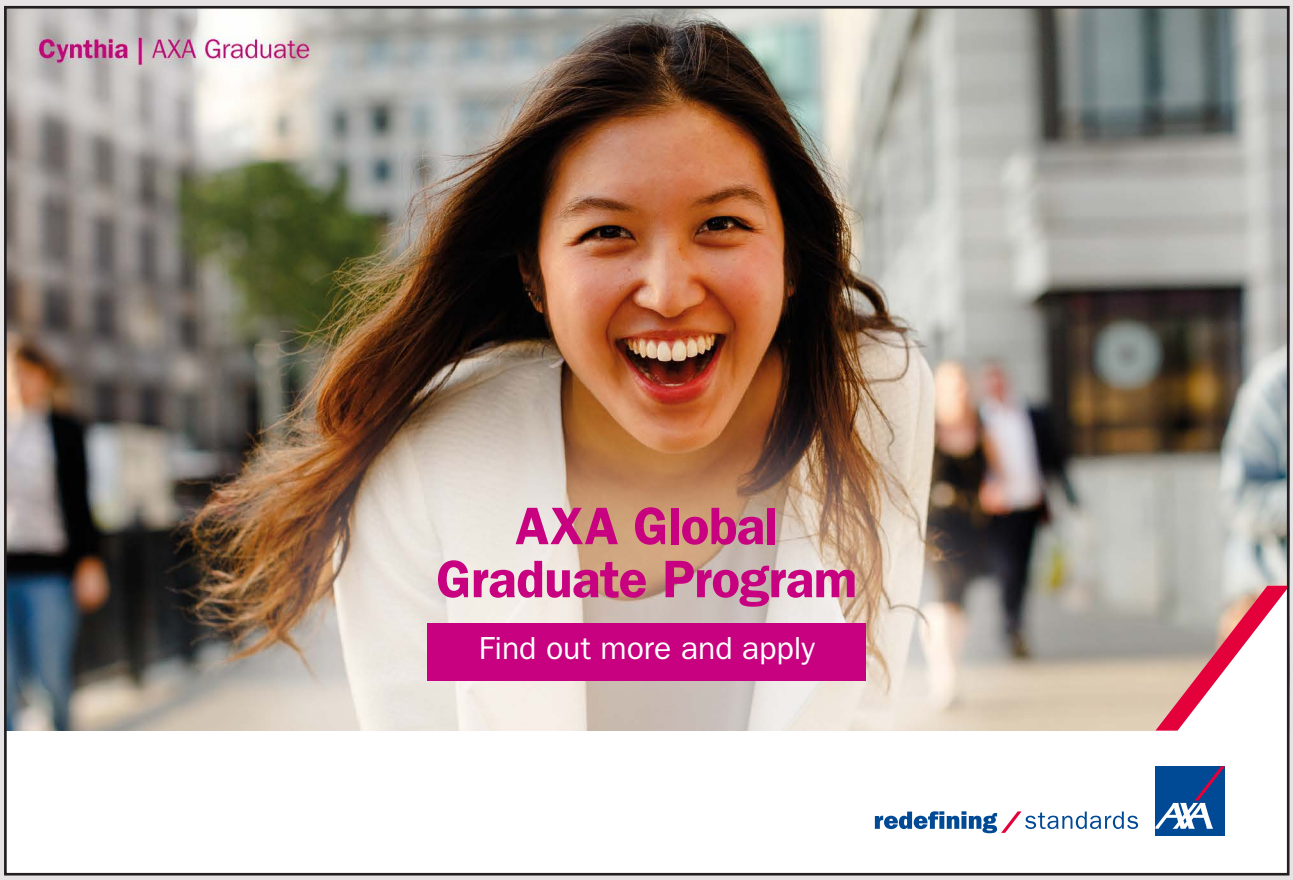
EES Solution:

First, write the EES Procedure:

```
PROCEDURE Ideal_isobaric_IdealGas(T2byT1, T1byT0:COP_i, WbyQ)

"Gives COP and Wby Q for Ideal, isobaric. source refrig … Source temp: from T1 to T2, Sink at Th"

"Inputs: T2byT1 = T2/T1, T1byT0 = T1/T0 … where T1 = refrign supplied from lower temp T1 to higher temp. T2,
heat rejected to sink temp at T0, all temps. in K"

"Outputs: COP_i, WbyQ (kJ/kJ)"

COP_i:= (T2byT1 – 1) / ((1 / T1byT0) * ln(T2byT1) – T2byT1 + 1)

WbyQ:= 1 / COP_i "[kJ/kg]"

END

"============================================================"
```



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Now, solve the problem:

T1 = 112 [K]

T2 = 190 [K]

T0 = 300 [K]

"Therefore:"

T2byT1 = T2 / T1

T1byT0 = T1 / T0

"Now, call the Procedure:"

CALL Ideal_isobaric_IdealGas(T2byT1, T1byT0:COP_i, WbyQ)

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP_i = 0.9683	T0 = 300 [K]	T1 = 112 [K]	T1byT0 = 0.3733
T2 = 190 [K]	T2byT1 = 1.696	WbyQ = 1.033 [kJ/kJ]	

Note the results:

COP = 0.9683, WbyQ = 1.033 kJ/kJ … Ans.

Now, to plot COP vs T1byT0 for different values of T2byT1:

First, compute the Parametric Table:

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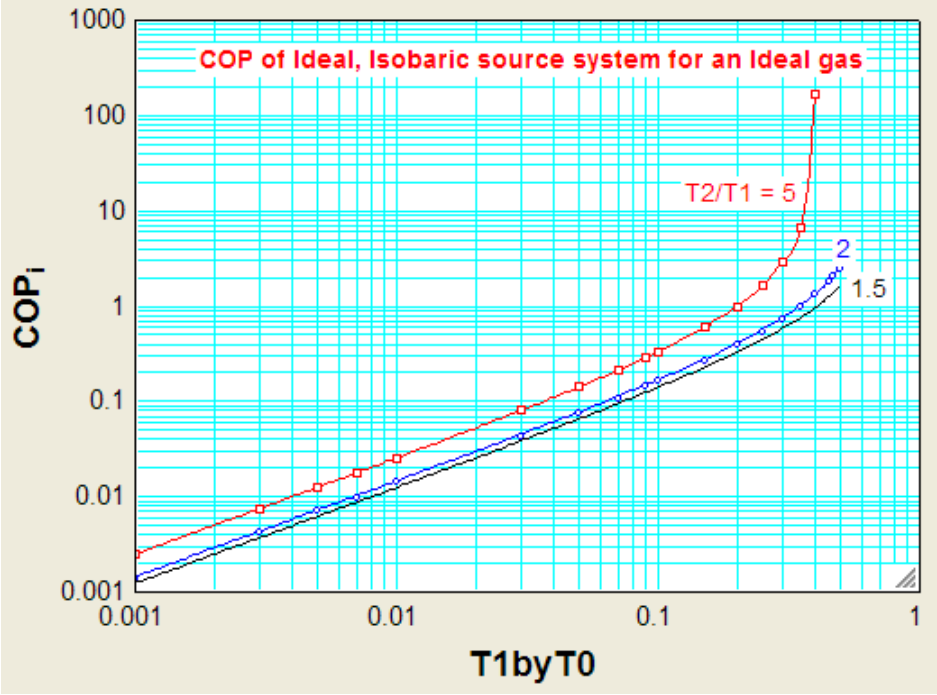
		T2/T1 = 1.5	T2/T1 = 2	T2/T1 = 5
1..19	T1byT0	COP_i	COP_i	COP_i
Run 1	0.001	0.001235	0.001445	0.002492
Run 2	0.003	0.003713	0.004347	0.007512
Run 3	0.005	0.006204	0.007266	0.01258
Run 4	0.007	0.008707	0.0102	0.01771
Run 5	0.01	0.01249	0.01464	0.02549
Run 6	0.03	0.03842	0.04524	0.08057
Run 7	0.05	0.06571	0.07774	0.1419
Run 8	0.07	0.09448	0.1123	0.2106
Run 9	0.09	0.1248	0.1492	0.2881
Run 10	0.1	0.1407	0.1686	0.3307
Run 11	0.15	0.227	0.2762	0.5944
Run 12	0.2	0.3274	0.4056	0.9883
Run 13	0.25	0.4457	0.5641	1.641
Run 14	0.3	0.5872	0.7631	2.931
Run 15	0.35	0.7593	1.02	6.685
Run 16	0.4	0.9734	1.365	169.5
Run 17	0.45	1.247	1.851	
Run 18	0.47	1.379	2.106	
Run 19	0.5	1.608	2.589	

And, now, plot the results:



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Prob. 4.3.4 An ideal, isobaric source refrigerator operates with 300 K as the sink temp, while the source temp varies between 70 K and 90 K. For an ideal gas, determine the COP. Compare this with the COP of a Carnot refrigerator operating between: (a) 300 K and 70 K (b) 300 K and 90 K. [1]

EES Solution:

"For Ideal, isobaric source refrigerator:"

T1 = 70 [K]

T2 = 90 [K]

T0 = 300 [K]

"Therefore:"

T2byT1 = T2 / T1

T1byT0 = T1 / T0

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"Now, call the Procedures:"

"For Isobaric source:"

CALL Ideal_isobaric_IdealGas(T2byT1, T1byT0:COP_i, WbyQ)

"For Carnot Refrigerator: between 300 K and 70 K"

Tc1 = 70 [K]

Th = 300 [K]

CALL Ideal_isoth(Tc1, Th:COP_i_1, W1byQ)

"For Carnot Refrigerator: between 300 K and 90 K"

Tc2 = 90 [K]

CALL Ideal_isoth(Tc2, Th:COP_i_2, W2byQ)

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP_i = 0.361	$COP_{i,1}$ = 0.3043	$COP_{i,2}$ = 0.4286	T0 = 300 [K]
T1 = 70 [K]	T1byT0 = 0.2333	T2 = 90 [K]	T2byT1 = 1.286
Tc1 = 70 [K]	Tc2 = 90 [K]	Th = 300 [K]	W1byQ = 3.286
W2byQ = 2.333	WbyQ = 2.77 [kJ/kJ]		

Thus:

For Isobaric source refrig.:

COP = 0.361 … Ans.

For Carnot refrig operating between 70 K and 300 K.:

COP_i_1 = 0.3043 … Ans.

For Carnot refrig operating between 90 K and 300 K.:

COP_i_2 = 0.4286 … Ans.

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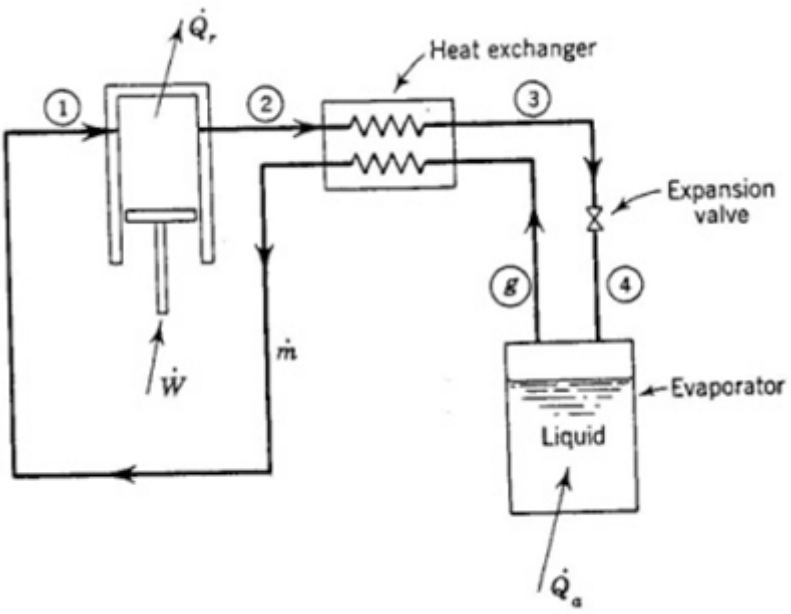
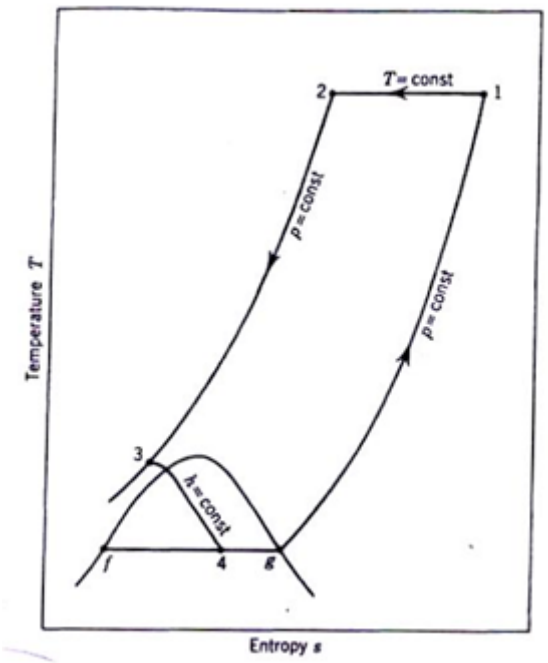
Prob. 4.3.5 Write an EES Procedure to find the parameters of a J-T Refrigeration system with various working fluids.





EES Procedure:

PROCEDURE JT_Refrign_system(Fluid$, P1, T1, P2, eta_co, eta_hx: Tsat_fluid, Qa_by_m, W_by_m, COP, COP_i, FOM)

"Gives various parameters for a JT refrign. system:"

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"Inputs: Fluid$: desired fluid (real)--- Nitrogen, Oxygen, Argon.
P1, P2 (kPa), T1 (K),

eta_co = compressor overall effcy., eta_hx = heat exchanger effcy."

"Outputs: Tsat_fluid (K), Qa_by_m (kJ/kg), W_by_m (kJ/kg), COP = Qa_by_W, COP_i, FOM = COP/COP_i"

h1:= ENTHALPY(Fluid$, T=T1, P=P1)
s1:= ENTROPY(Fluid$, T=T1, P=P1)

h2 := ENTHALPY(Fluid$, T=T1, P=P2)
s2 := ENTROPY(Fluid$, T=T1, P=P2)

hg := ENTHALPY(Fluid$, x=1, P=P1)

Tsat_fluid := T_sat(Fluid$, P = P1)

W_by_m := (T1 * (s1 – s2) – (h1 – h2)) / eta_co

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Qa_by_m := (h1 – h2) – (1 – eta_hx) * (h1 – hg)

COP := Qa_by_m / W_by_m

COP_i:= Tsat_fluid / (T1 – Tsat_fluid)

FOM:= COP / COP_i

END

"=="

"**Prob. 4.3.6** In a J-T Refrigeration system with Nitrogen as working fluid, the system works between 0.5 bar, 300 K and 152 bar, with isothermal compression. Overall efficiency of compressor is 70%, and heat exchangers effcy is 96.5%. Find out the refrig. effect, work required, COP and FOM."

EES Solution:

Fluid$ = 'Nitrogen';

P1 = 0.5 * 100 [kPa]

T1 = 300 [K]

P2 = 152 * 100 [kPa]

eta_co = 0.7

eta_hx = 0.965

CALL JT_Refrign_system(Fluid$, P1, T1, P2, eta_co, eta_hx: Tsat_fluid, Qa_by_m, W_by_m, COP, COP_i, FOM)

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP = 0.02555	COP_i = 0.3148	η_{co} = 0.7
η_{hx} = 0.965	Fluid$ = 'Nitrogen'	FOM = 0.08116
P1 = 50 [kPa]	P2 = 15200 [kPa]	$Qa_{by,m}$ = 18.58 [kJ/kg]
T1 = 300 [K]	$Tsat_{fluid}$ = 71.83 [K]	$W_{by,m}$ = 727.1 [kJ/kg]

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Thus:

Refrig. effect = Qa_by_m = 18.58 kJ/kg … Ans.

Work required = W_by_m = 727.1 kJ/kg … Ans.

COP = 0.02555 … Ans.

COP_i = 0.3148 … Ans.

FOM = 0.8116 … Ans.

Plot COP against compressor effcy, as the compressor effcy varies from 0.6 to 1, for eta_HX values of 0.96, 0.98 and 1:

First, compute the Parametric Table:

		eta_hx = 0.96	eta_hx = 0.98	eta_hx = 1
1..9	1 η_{co}	2 COP	2 COP	2 COP
Run 1	0.6	0.02049	0.02612	0.03174
Run 2	0.65	0.0222	0.0283	0.03439
Run 3	0.7	0.02391	0.03047	0.03704
Run 4	0.75	0.02562	0.03265	0.03968
Run 5	0.8	0.02732	0.03483	0.04233
Run 6	0.85	0.02903	0.037	0.04497
Run 7	0.9	0.03074	0.03918	0.04762
Run 8	0.95	0.03245	0.04135	0.05026
Run 9	1	0.03416	0.04353	0.05291

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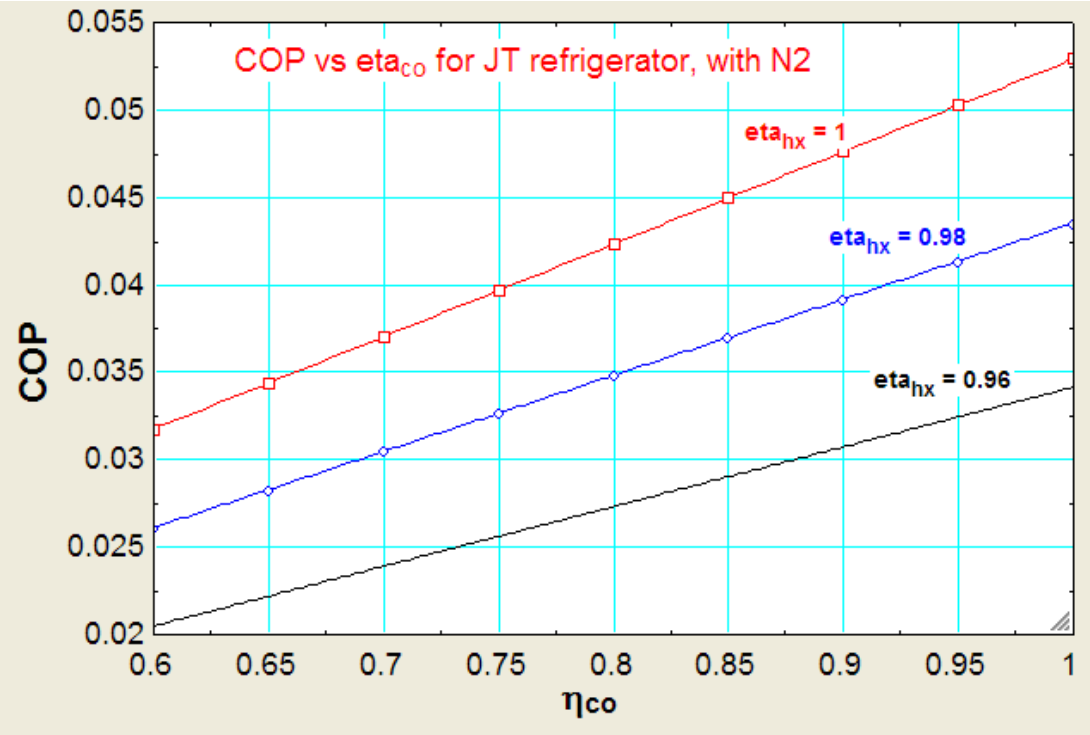
Now, plot the results:



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Prob. 4.3.7 In a J-T Refrigeration system with Argon as working fluid, the system works between 1.013 bar, 300 K and 202.6 bar, with isothermal compression. Efficiencies of compressor and heat exchangers are 72% and 98% respectively. Find out the refrig. effect, work required, COP and FOM.

EES Solution:

```
Fluid$ = 'Argon';

P1 = 1.013 * 100 [kPa]

T1 = 300 [K]

P2 = 202.6 * 100 [kPa]

eta_co = 0.72

eta_hx = 0.98

CALL JT_Refrign_system(Fluid$, P1, T1, P2, eta_co, eta_hx: Tsat_fluid, Qa_by_m, W_by_m, COP, COP_i, FOM)
```

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP = 0.06629	COP_i = 0.4104	η_{co} = 0.72
η_{hx} = 0.98	Fluid$ = 'Argon'	FOM = 0.1615
P1 = 101.3 [kPa]	P2 = 20260 [kPa]	$Qa_{by,m}$ = 29.96 [kJ/kg]
T1 = 300 [K]	$Tsat_{fluid}$ = 87.3 [K]	$W_{by,m}$ = 451.9 [kJ/kg]

Thus:

Refrig. effect = Qa_by_m = 29.96 kJ/kg … Ans.

Work required = W_by_m = 451.9 kJ/kg … Ans.

COP = 0.06629 … Ans.

COP_i = 0.4104 … Ans.

FOM = 0.1615 … Ans.

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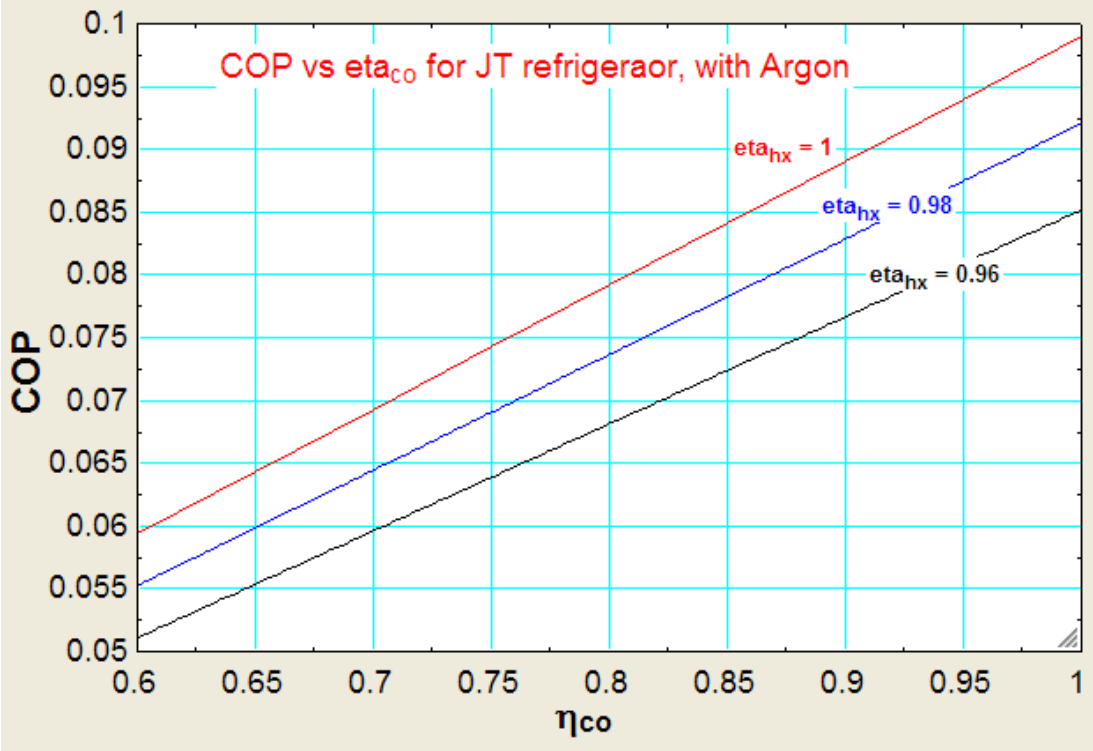
Plot COP against compressor effcy, as the compressor effcy varies from 0.6 to 1, for eta_HX values of 0.96, 0.98 and 1:

First, compute the Parametric Table:

		eta_hx = 0.96	eta_hx = 0.98	eta_hx = 1
1..9	1 η_{co}	2 COP	2 COP	2 COP
Run 1	0.6	0.0511	0.05524	0.05939
Run 2	0.65	0.05536	0.05985	0.06434
Run 3	0.7	0.05962	0.06445	0.06929
Run 4	0.75	0.06388	0.06905	0.07423
Run 5	0.8	0.06813	0.07366	0.07918
Run 6	0.85	0.07239	0.07826	0.08413
Run 7	0.9	0.07665	0.08287	0.08908
Run 8	0.95	0.08091	0.08747	0.09403
Run 9	1	0.08517	0.09207	0.09898

Now, plot the results:



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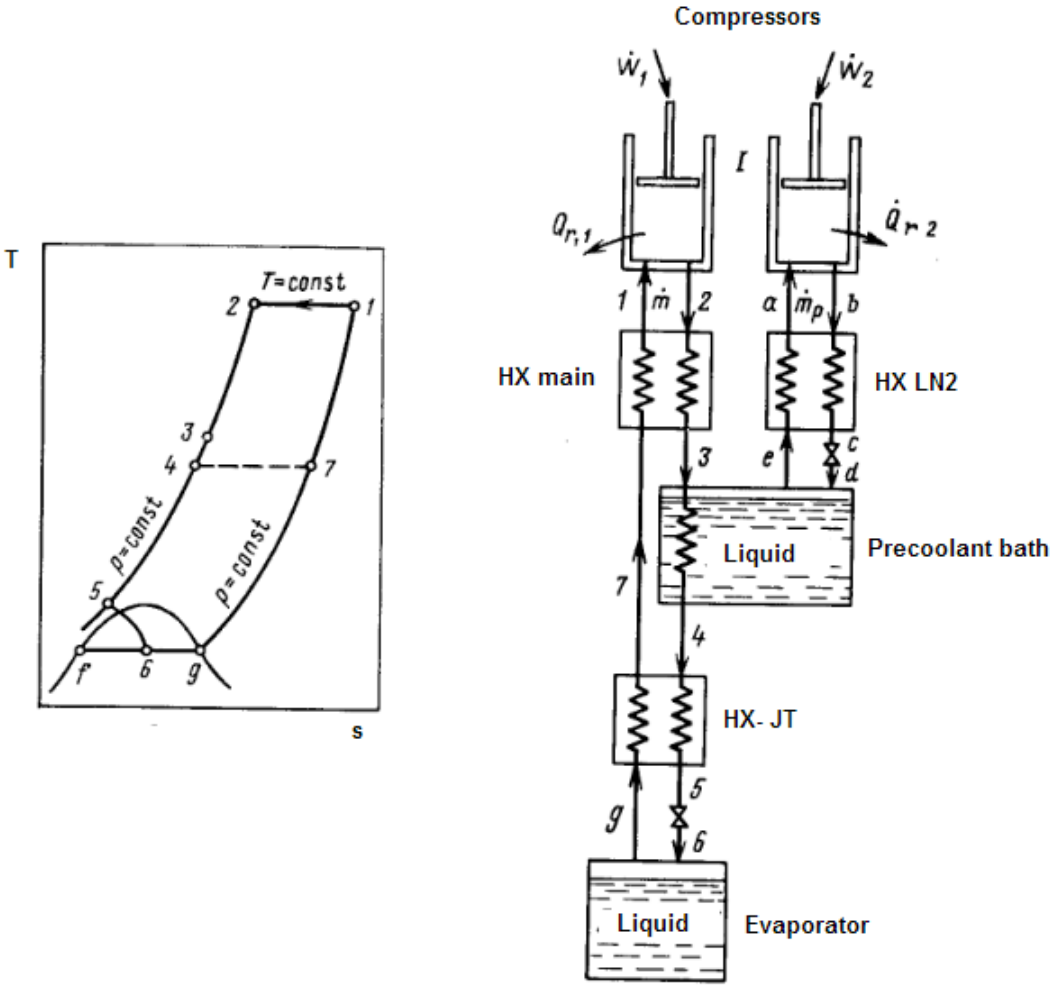
Prob. 4.3.8 Write an EES Procedure to find the various parameters in a pre-cooled JT refrigeration system with H2 as the working fluid and N2 as the pre-coolant.



EES Procedure:

PROCEDURE Precooled_JT_H2(P1, T1, P2, P1N2, T1N2, P2N2, eta_cH2, eta_cN2, eta_HX_main, eta_HX_N2, eta_HX_JT: Tsat_N2, z, Qa_by_m, W_by_m, COP, COP_i, FOM)

"Gives various parameters for a Nitrogen pre-cooled JT refrign. system for Hydrogen:"

"Inputs: P1, P2, P1N2, P2N2 (kPa), T1, T1N2 (K),
eta_cN2, eta_cH2 = compressor effcy for N2 and H2., eta_HX_main = main heat exchanger effcy, eta_HX_N2 = N2 heat exchanger effcy, eta_HX_JT = JTheat exchanger effcy"

"Outputs: Tsat_N2 (K), z = (m_N2/m_H2), Qa_by_m (kJ/kg), W_by_m (kJ/kg), COP = Qa_by_W, COP_i, FOM = COP/COP_i"

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h1:= ENTHALPY(Hydrogen, T=T1, P=P1)
s1:= ENTROPY(Hydrogen, T=T1, P=P1)

h2 := ENTHALPY(Hydrogen, T=T1, P=P2)
s2 := ENTROPY(Hydrogen, T=T1, P=P2)

hg := ENTHALPY(Hydrogen, x=1, P=P1)

ha := ENTHALPY(Nitrogen, T=T1N2, P=P1N2)

hb := ENTHALPY(Nitrogen, T=T1N2, P=P2N2)

sa := ENTROPY(Nitrogen, T=T1N2, P=P1N2)

sb := ENTROPY(Nitrogen, T=T1N2, P=P2N2)

he := Enthalpy(Nitrogen, x=1, P=P1N2)

Tsat_N2 := T_sat(Nitrogen, P = P1N2)

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T7 :=Tsat_N2

h7 := ENTHALPY(Hydrogen, T=T7, P=P1)

h4 := ENTHALPY(Hydrogen, T=T7, P=P2)

Qa_by_m := (h7 – h4) – (1 – eta_HX_JT) * (h7 – hg)

z := (Qa_by_m – ((h1 – h2) – (1 – eta_HX_main) * (h1 – hg))) / ((ha – hb) – (1 -eta_HX_N2) * (ha – he))

AA := T1 * (s1 – s2) – (h1 – h2)

BB := T1N2 * (sa – sb) – (ha – hb)

W_by_m :=AA / eta_cH2 + z * BB / eta_cN2

COP := Qa_by_m / W_by_m

TL := T_sat(Hydrogen, P = P1)

COP_i:= TL / (T1 – TL)

FOM:= COP / COP_i

END

"=="

Prob. 4.3.9 Determine the refrig. effect, COP, and FOM for a pre-cooled JT liquid hydrogen refrigerator, if the hydrogen is compressed between 101.3 kPa and 8.1 MPa and 300 K. The nitrogen is compressed between 101.3 kPa and 15.2 MPa and 300 K. The main HX has an effectiveness of 0.99 and the pre-coolant HX has an effectiveness of 0.98. The cold HX (or the JT HX) in the hydrogen circuit has an effectiveness of 0.96 and both the compressors may be assumed 100% efficient. [1]

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EES Solution:

We use the above written EES Procedure:

P1 = 101.3 [kPa]

P2 = 8.1E03 [kPa]

T1 = 300 [K]

P1N2 = 101.3 [kPa]

P2N2 = 15.2E03 [kPa]

T1N2 = 300 [K]

eta_HX_main = 0.99

eta_HX_N2 = 0.98

eta_HX_JT = 0.96

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eta_cH2 = 1

eta_cN2 = 1

CALL Precooled_JT_H2(P1, T1, P2, P1N2, T1N2, P2N2, eta_cH2, eta_cN2, eta_HX_main, eta_HX_N2, eta_HX_JT: Tsat_N2, z, Qa_by_m, W_by_m, COP, COP_i, FOM)

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

$COP = 0.01375$	$COP_i = 0.07292$	$\eta_{cH2} = 1$	$\eta_{cN2} = 1$
$\eta_{HX,JT} = 0.96$	$\eta_{HX,main} = 0.99$	$\eta_{HX,N2} = 0.98$	$FOM = 0.1885$
$P1 = 101.3$ [kPa]	$P1N2 = 101.3$ [kPa]	$P2 = 8100$ [kPa]	$P2N2 = 15200$ [kPa]
$Qa_{by,m} = 133.4$ [kJ/kg]	$T1 = 300$ [K]	$T1N2 = 300$ [K]	$Tsat_{N2} = 77.35$ [K]
$W_{by,m} = 9706$ [kJ/kg]	$z = 9.471$		

Thus:

Refrig. effect = Qa_by_m = 133.4 kJ/kg … ns.

COP = 0.01375 … Ans.

FOM = 0.1885 … Ans.

"**Prob. 4.3.10** Determine the refrig. effect, COP, and FOM for a pre-cooled JT liquid hydrogen refrigerator, if the hydrogen is compressed between 101.3 kPa and 10.13 MPa and 300 K. The nitrogen is compressed between 101.3 kPa and 20.3 MPa and 300 K. The main HX has an effectiveness of 0.98 and the pre-coolant HX has an effectiveness of 0.97. The cold HX (or the JT HX) in the hydrogen circuit has an effectiveness of 0.95 and both the compressors may be assumed 75% efficient. [1]"

EES Solution:

We use the above written EES Procedure:

P1 = 101.3 [kPa]

P2 = 10.13E03 [kPa]

T1 = 300 [K]

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P1N2 = 101.3 [kPa]

P2N2 = 20.3E03 [kPa]

T1N2 = 300 [K]

eta_HX_main = 0.98

eta_HX_N2 = 0.97

eta_HX_JT = 0.95

eta_cH2 = 0.75

eta_cN2 =0.75

CALL Precooled_JT_H2(P1, T1, P2, P1N2, T1N2, P2N2, eta_cH2, eta_cN2, eta_HX_main, eta_HX_N2, eta_HX_JT: Tsat_N2, z, Qa_by_m, W_by_m, COP, COP_i, FOM)

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP = 0.01018	COP_i = 0.07292	η_{cH2} = 0.75	η_{cN2} = 0.75
$\eta_{HX,JT}$ = 0.95	$\eta_{HX,main}$ = 0.98	$\eta_{HX,N2}$ = 0.97	FOM = 0.1396
P1 = 101.3 [kPa]	P1N2 = 101.3 [kPa]	P2 = 10130 [kPa]	P2N2 = 20300 [kPa]
$Qa_{by,m}$ = 146.4 [kJ/kg]	T1 = 300 [K]	T1N2 = 300 [K]	$Tsat_{N2}$ = 77.35 [K]
$W_{by,m}$ = 14381 [kJ/kg]	z = 10.6		

Thus:

Refrig. effect = Qa_by_m = 146.4 kJ/kg … Ans.

COP = 0.01018 … Ans.

FOM = 0.1396 … Ans.

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Also, plot the effect of variation of eta_HX_JT on various parameters, if other conditions remain the same:

First, compute the Parametric Table:

1..11	1 $\eta_{HX,JT}$	2 $Qa_{by,m}$ [kJ/kg]	3 COP	4 FOM	5 z
Run 1	0.95	146.4	0.01018	0.1396	10.6
Run 2	0.955	149.4	0.01033	0.1417	10.72
Run 3	0.96	152.4	0.01049	0.1439	10.84
Run 4	0.965	155.5	0.01064	0.146	10.96
Run 5	0.97	158.5	0.0108	0.148	11.08
Run 6	0.975	161.6	0.01095	0.1501	11.2
Run 7	0.98	164.6	0.0111	0.1522	11.32
Run 8	0.985	167.6	0.01124	0.1542	11.44
Run 9	0.99	170.7	0.01139	0.1562	11.56
Run 10	0.995	173.7	0.01153	0.1582	11.68
Run 11	1	176.8	0.01168	0.1601	11.8

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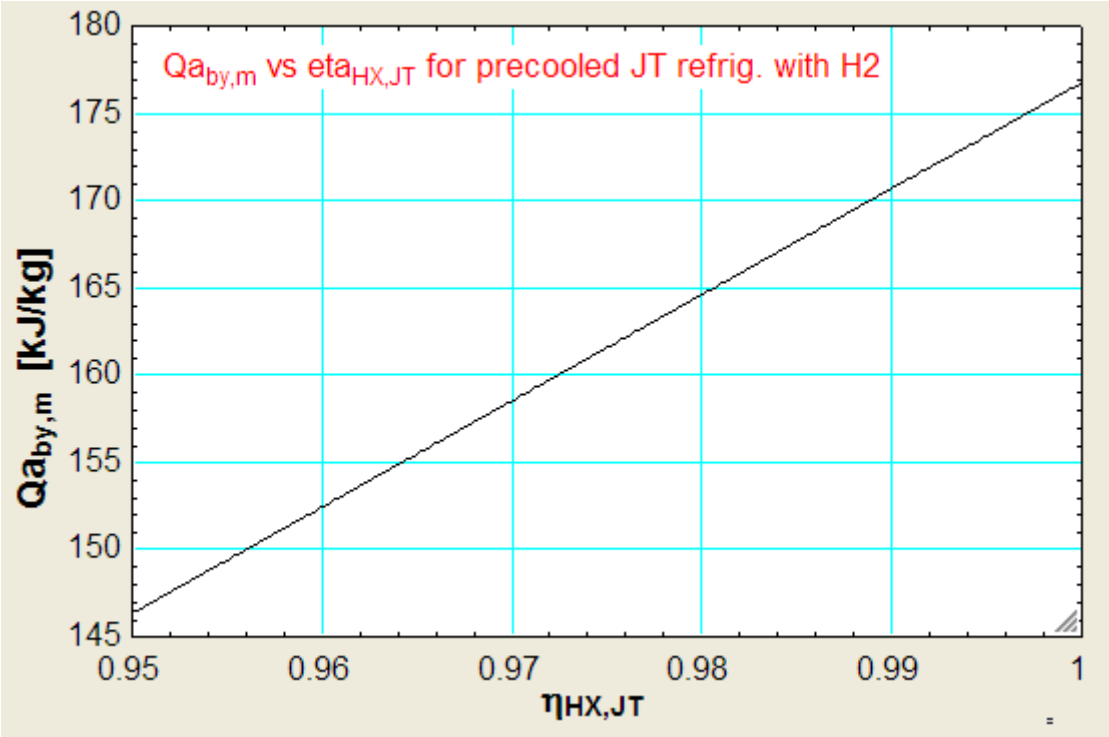

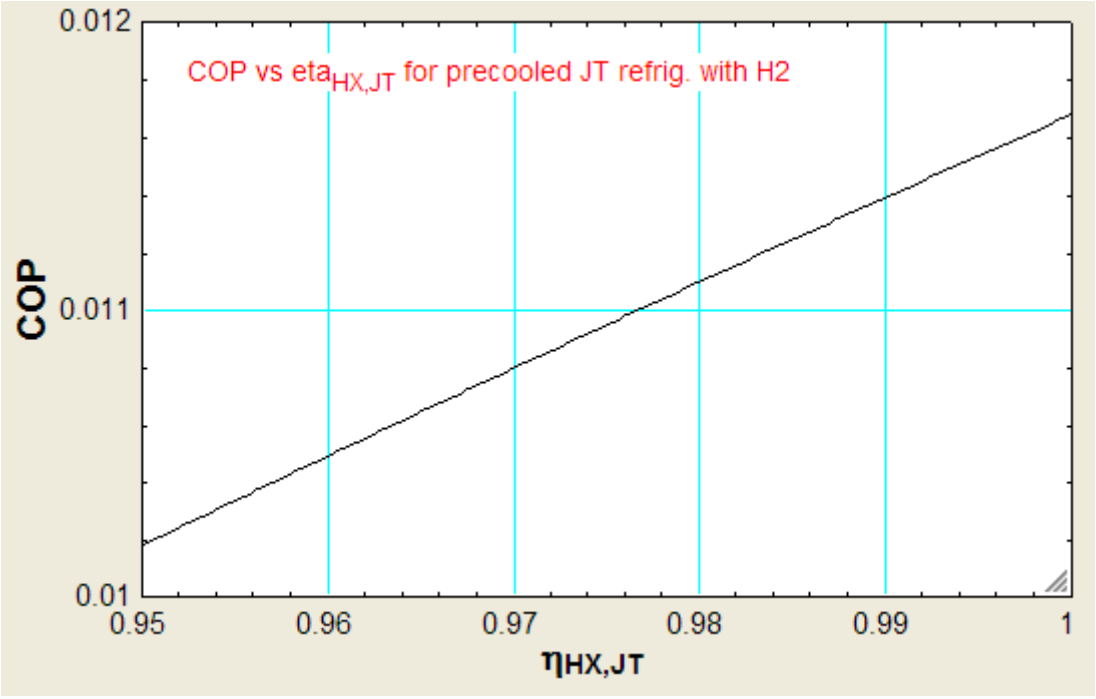

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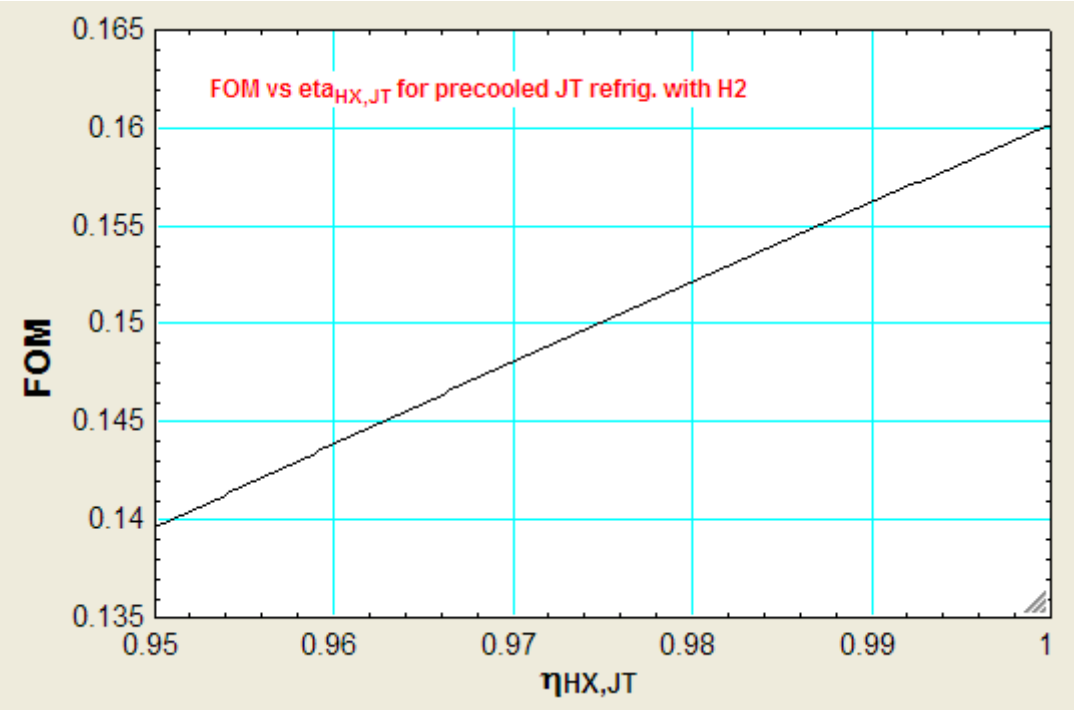

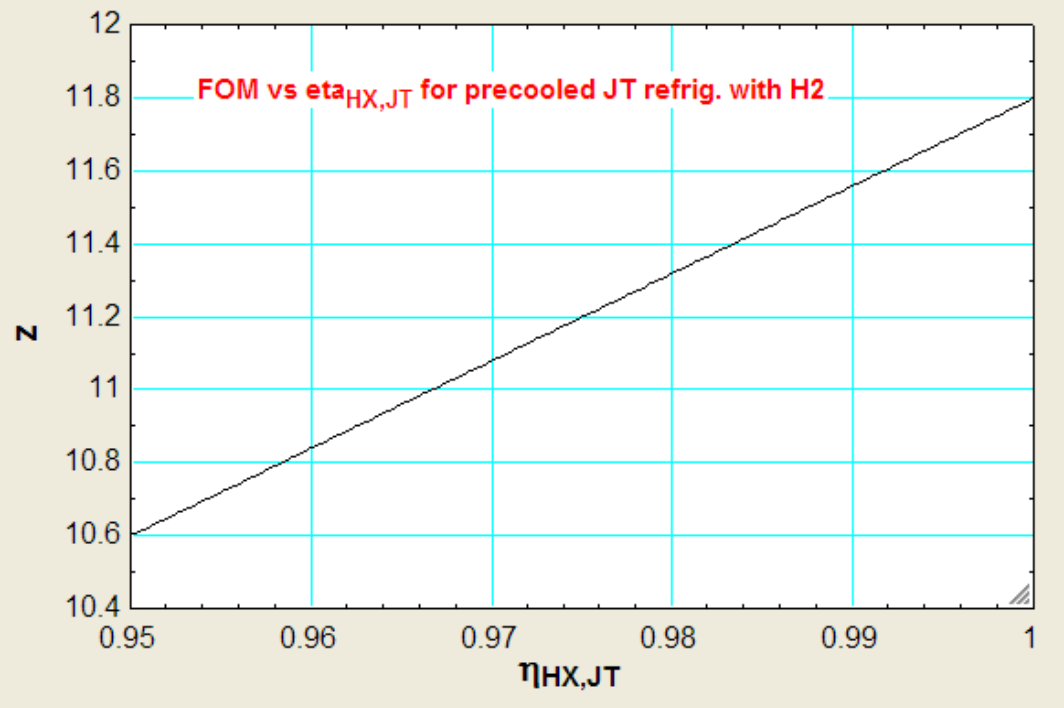

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Prob. 4.3.11 Determine the refrig. effect, COP, and FOM for a pre-cooled JT liquid hydrogen refrigerator, if the hydrogen is compressed between 1.013 bar and 152 bar and 294 K. The nitrogen is compressed between 1.013 bar and 202.6 bar and 294 K. The nitrogen flow rate ratio (z) is 5. The main HX and the pre-coolant HX have an effectiveness of 100% each. Find the effectiveness of cold HX (or the JT HX) in the hydrogen circuit if both the compressors are 100% efficient. [1]

EES Solution:

We shall use the EES Procedure for Pre-cooled HT refrig. written earlier:

P1 = 101.3 [kPa]

P2 = 152E02 [kPa]

T1 = 294 [K]

P1N2 = 101.3 [kPa]

P2N2 = 202.6E02 [kPa]

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T1N2 = 294 [K]

eta_HX_main = 1

eta_HX_N2 = 1

eta_cH2 = 1

eta_cN2 =1

z = 5

eta_HX_JT = ?

CALL Precooled_JT_H2(P1, T1, P2, P1N2, T1N2, P2N2, eta_cH2, eta_cN2, eta_HX_main, eta_HX_N2, eta_HX_JT: Tsat_N2, z, Qa_by_m, W_by_m, COP, COP_i, FOM)

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP = 0.01077	COP_i = 0.07452	η_{cH2} = 1
η_{cN2} = 1	$\eta_{HX,JT}$ = 0.8323	$\eta_{HX,main}$ = 1
$\eta_{HX,N2}$ = 1	FOM = 0.1445	P1 = 101.3 [kPa]
P1N2 = 101.3 [kPa]	P2 = 15200 [kPa]	P2N2 = 20260 [kPa]
$Qa_{by,m}$ = 91.55 [kJ/kg]	T1 = 294 [K]	T1N2 = 294 [K]
$Tsat_{N2}$ = 77.35 [K]	$W_{by,m}$ = 8502 [kJ/kg]	z = 5

Thus:

Effectiveness of JT HX = eta_HX_JT = 0.8323 … Ans.

Note: Note the ease with which this result is obtained in EES.

Prob. 4.3.12 Write an EES Procedure to find the various parameters in a Claude refrigeration system, where a fraction x of the gas compressed in the compressor is sent through the expander.

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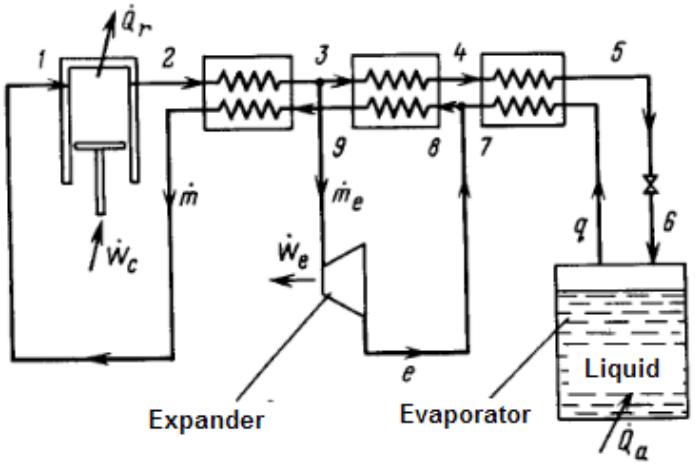

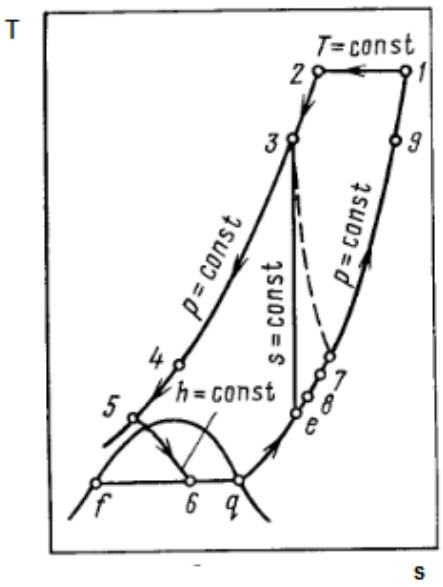

EES Procedure:

PROCEDURE Claude_refrig(Fluid$, P1, T1, P2, T3, eta_co, eta_e_ad, eta_em, Fraction_x: Tsat_fluid, Qa_by_m, W_by_m, COP, COP_i, FOM)

"Gives various parameters for a Claude refrign. system for a given Fluid"

"Inputs: P1, P2, (kPa), T1, T3 (K),
eta_co= compressor effcy ., , eta_e_ad = adab. effcy of expander, , eta_em = mech. effcy of expander, Fraction_x = fraction of the gas compressed that goes through the expander"

"Outputs: Tsat_fluid (K), Qa_by_m (kJ/kg), W_by_m (kJ/kg), COP = Qa_by_W, COP_i, FOM = COP/COP_i"

h1:= ENTHALPY(Fluid$, T=T1, P=P1)
s1:= ENTROPY(Fluid$, T=T1, P=P1)

h2 := ENTHALPY(Fluid$, T=T1, P=P2)
s2 := ENTROPY(Fluid$, T=T1, P=P2)

h3 := ENTHALPY(Fluid$, T=T3, P=P2)
s3 := ENTROPY(Fluid$, T=T3, P=P2)

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se := s3

he := ENTHALPY(Fluid$, s=se, P=P1)

Tsat_fluid := T_sat(Fluid$, P = P1)

Qa_by_m := (h1 – h2) + Fraction_x * eta_e_ad * (h3 – he)

AA := (T1 * (s1 – s2) – (h1 – h2)) / eta_co

BB := Fraction_x * eta_e_ad * eta_em * (h3 – he)

W_by_m :=AA – BB

COP := Qa_by_m / W_by_m

TL := Tsat_fluid

COP_i:= TL / (T1 – TL)

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• 2nd place: MSc Global Supply Chain Management and Change
Sources: Keuzegids Master ranking 2013; Elsevier 'Beste Studies' ranking 2012; Financial Times Global Masters in Management ranking 2012
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FOM:= COP / COP_i

END

"=="

Prob. 4.3.13 In an ideal Claude refrigeration system using nitrogen as the working fluid, the gas enters the reversible isothermal compressor at 1.013 bar, and 300 K, and is compressed to 40.5 bar. Determine the expander mass flow rate ratio (x = me/m) required to result in a refrigeration effect of 80 kJ/kg, if the gas enters the reversible adiabatic expander at 4.5 bar and 240 K. [1]

EES Solution:

Using the EES Procedure written above:

Fluid$ = 'Nitrogen'

P1 = 101.3 [kPa]

T1 = 300 [K]

P2 = 4050 [kPa]

T3 = 240 [K]

eta_co = 1

eta_e_ad = 1

eta_em = 1

Qa_by_m = 80 [kJ/kg]

CALL Claude_refrig(Fluid$, P1, T1, P2, T3, eta_co, eta_e_ad, eta_em, Fraction_x: Tsat_fluid, Qa_by_m, W_by_m, COP, COP_i, FOM)

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Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP = 0.3121	COP_i = 0.3474	η_{co} = 1	η_{em} = 1
$\eta_{e,ad}$ = 1	Fluid$ = 'Nitrogen'	FOM = 0.8984	$Fraction_x$ = 0.4675
P1 = 101.3 [kPa]	P2 = 4050 [kPa]	$Qa_{by,m}$ = 80 [kJ/kg]	T1 = 300 [K]
T3 = 240 [K]	$Tsat_{fluid}$ = 77.35 [K]	$W_{by,m}$ = 256.3 [kJ/kg]	

Thus:

Fraction_x = 0.4675 to get a refrign of Qa_by_m = 80 kJ/kg … Ans.

Further:

COP = 0.3121 … Ans.

FOM = 0.8984 … Ans.

Plot the refrig. effect and COP against Fraction_x as Fraction_x varies from 0.1 to 0.6:

First, compute the Parametric Table:

1..11	1 $Fraction_x$	2 $Qa_{by,m}$ [kJ/kg]	3 COP
Run 1	0.1	23.68	0.07574
Run 2	0.15	31.34	0.1028
Run 3	0.2	39	0.1312
Run 4	0.25	46.67	0.1611
Run 5	0.3	54.33	0.1927
Run 6	0.35	61.99	0.226
Run 7	0.4	69.65	0.2612
Run 8	0.45	77.32	0.2985
Run 9	0.5	84.98	0.3381
Run 10	0.55	92.64	0.3802
Run 11	0.6	100.3	0.425

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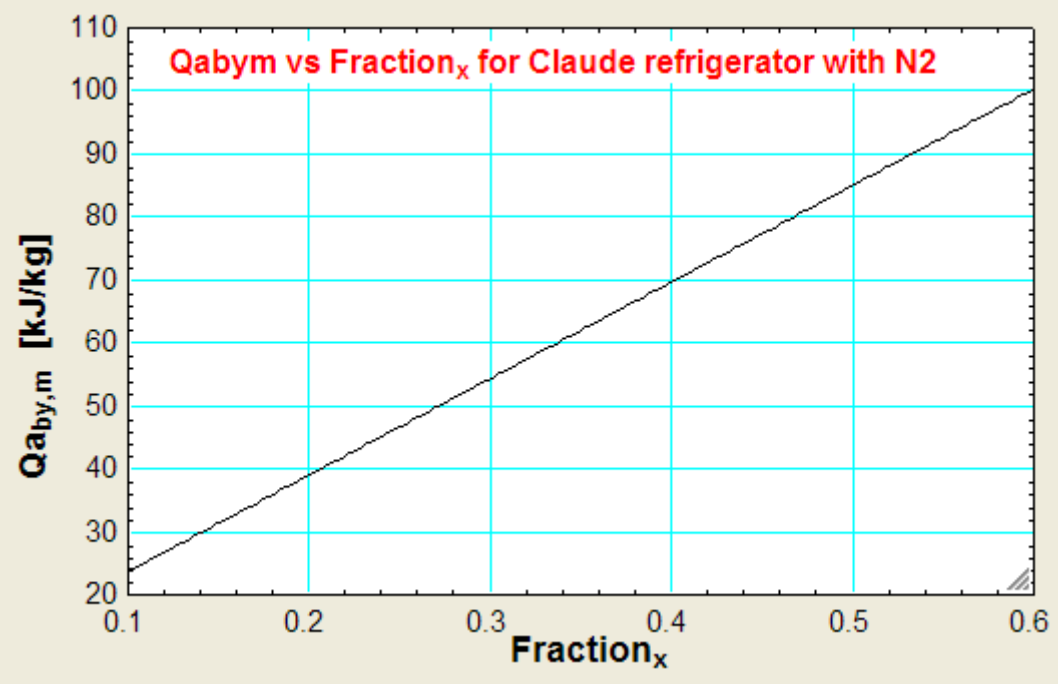
Now, plot the results:



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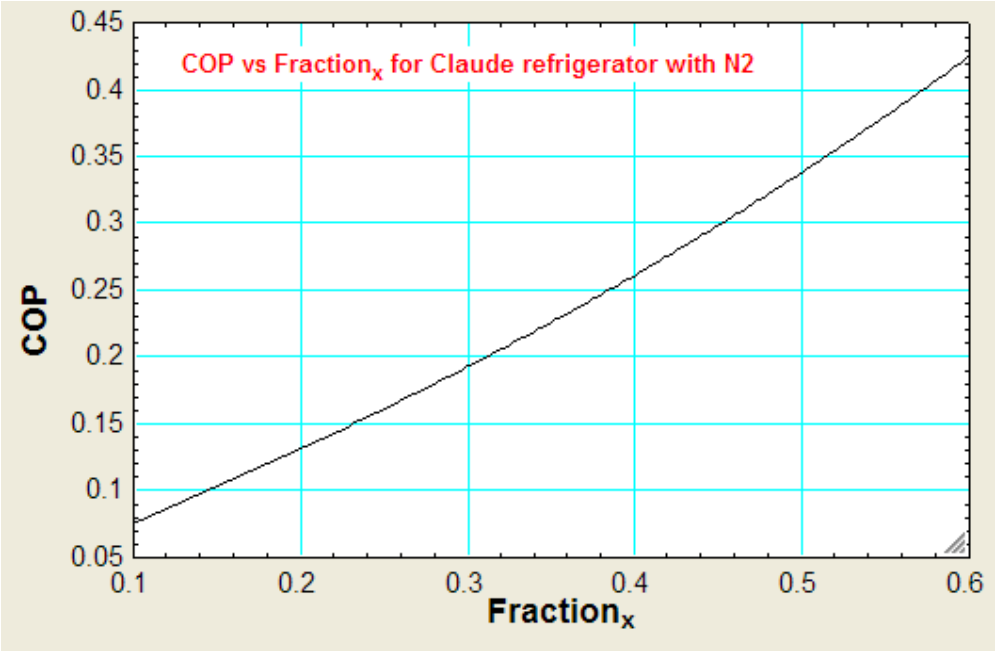

Prob.4.3.14 In the above problem, if the compressor overall efficiency is 75%, adiabatic efficiency and mech. efficiency of expander are 80% and 90%, other quantities remaining the same, find the refrig. effect and COP.

EES Solution:

Fluid$ = 'Nitrogen'

P1 = 101.3 [kPa]

T1 = 300 [K]

P2 = 4050 [kPa]

T3 = 240 [K]

eta_co = 0.75

eta_e_ad = 0.8

eta_em = 0.9

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Fraction_x = 0.4675 "…from previous problem, i.e. Prob.4.3.13"

CALL Claude_refrig(Fluid$, P1, T1, P2, T3, eta_co, eta_e_ad, eta_em, Fraction_x: Tsat_fluid, Qa_by_m, W_by_m, COP, COP_i, FOM)

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP = 0.1703	COP$_i$ = 0.3474	η_{co} = 0.75	η_{em} = 0.9
$\eta_{e,ad}$ = 0.8	Fluid$ = 'Nitrogen'	FOM = 0.4901	Fraction$_x$ = 0.4675
P1 = 101.3 [kPa]	P2 = 4050 [kPa]	Qa$_{by,m}$ = 65.67 [kJ/kg]	T1 = 300 [K]
T3 = 240 [K]	Tsat$_{fluid}$ = 77.35 [K]	W$_{by,m}$ = 385.7 [kJ/kg]	

Thus:

Refrign effect = Qa_by_m = 65.67 kJ/kg … Ans.

COP = 0.1703 … Ans.

FOM = 0.4901 … Ans.

Prob.4.3.15 In a refrigeration system with a wet gas expander (see the fig.), the working fluid is helium, which enters the main compressor at 270 K and 4.053 bar. Compressors and expanders may be assumed to have efficiencies as shown below. At point 3, 30% of the main stream is by-passed to the main expander at a temp of 200 K and 40.53 bar. The helium gas leaves the main compressor at 300 K and 40.53 bar. The helium enters the low temp compressor at 1.013 bar and sat. vapor conditions and leaves at 4.053 bar. Determine the coeff. of performance and the FOM. [1]

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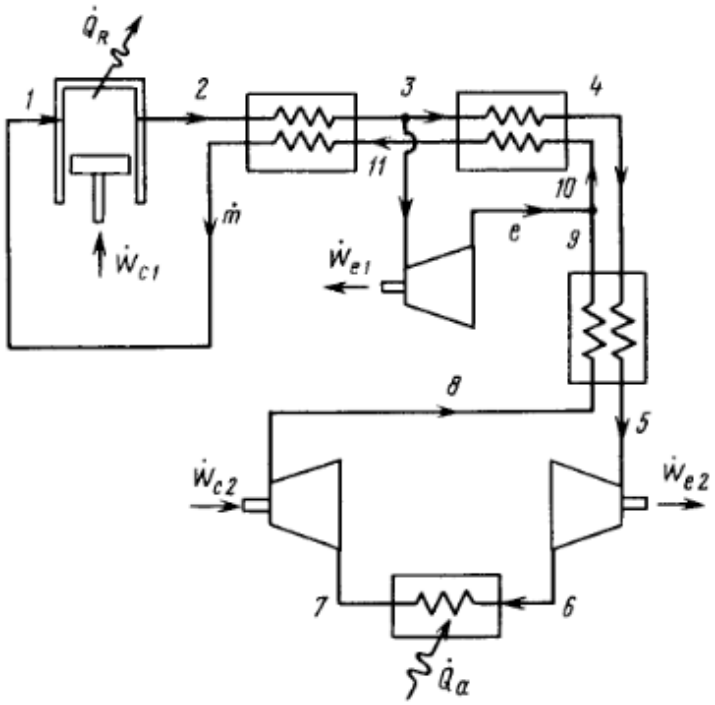

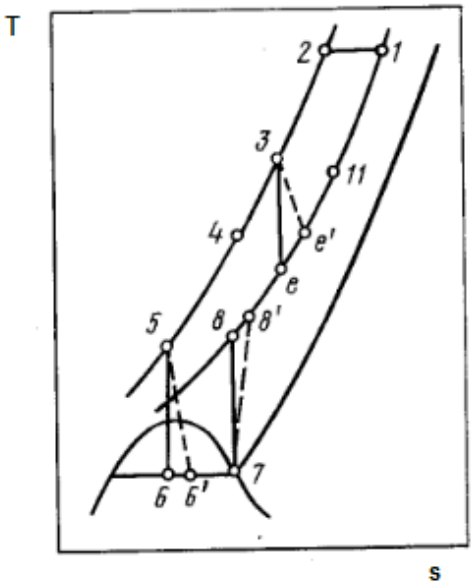

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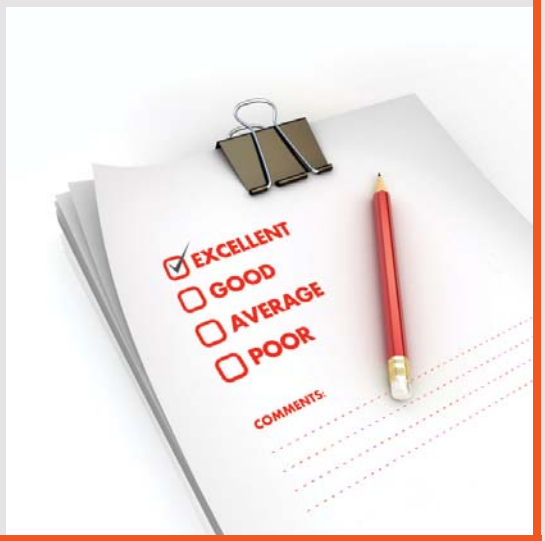

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First, write an EES Procedure to calculate various parameters for a "Cold gas refrigeration system":

PROCEDURE Coldgas_refrig_He(P1, T1, P2, T2, T3, P7, Fraction_x, eta_co, eta_c, eta_ad_e1, eta_m_e1, eta_ad_e2: T7, Qa_by_m, Wc1_by_m, Wc2_by_m,We1_by_m, We2_by_m, Wnet_by_m, COP, COP_i, FOM)

"Gives various parameters for a Cold gas refrign. system for Helium as working fluid"

"Inputs: P1, P2, P7 (kPa), T1, T2,T3 (K),
eta_co= compressor overall effcy .,eta_c = effcy of wet compressor, eta_ad_e1 = adab. effcy of expander 1, , eta_m_e1 = mech. effcy of expander 1, eta_ad_e2 = adab. effcy of wet expander, Fraction_x = fraction of the gas compressed that goes through the expander,"

"Outputs: T7 (K), Qa_by_m (kJ/kg), We1_by_m, We2_by_m, Wc1_by_m, Wc2_by_m, Wnet_by_m (kJ/kg), COP, COP_i, FOM"

h1:= ENTHALPY(Helium, T=T1, P=P1)
s1:= ENTROPY(Helium, T=T1, P=P1)

h2 := ENTHALPY(Helium, T=T2, P=P2)
s2 := ENTROPY(Helium, T=T2, P=P2)

P3 := P2
P5 := P2
P8 := P1

T7 := T_sat(Helium, P = P7)
h3 := ENTHALPY(Helium, T=T3, P=P3)
s3 := ENTROPY(Helium, T=T3, P=P3)

se := s3

he := ENTHALPY(Helium, s=se, P=P8)

h7 := Enthalpy(Helium, x=1, P=P7)
s7 := Entropy(Helium, x=1, P=P7)

sg := s7

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s8:= s7

h8 := ENTHALPY(Helium, s=s8, P=P8)

sf := Entropy(Helium, x=0, P=P7)

he_prime := h3 – eta_ad_e1 * (h3 – he)

h8_prime := h7 + (h8 – h7) / eta_c

AA := (h2 – h1) – Fraction_x * (h3 -he_prime)

h5 := AA / (1 – Fraction_x) + h8_prime

s5=Entropy(Helium,h=h5,P=P5)

x6 := (sg – s5) / (sg – sf)

hg := Enthalpy(Helium,x=1,P=P7)

hf := Enthalpy(Helium,x=0,P=P7)

h6 := hg – x6 * (hg – hf)

h6_prime := h5 – eta_ad_e2 * (h5 – h6)

Qa_by_m := (1 – Fraction_x) * (h7 – h6_prime)

Wc1_by_m := (T2 * (s1 – s2) – (h1 – h2)) / eta_co "…if main expander work is utilised to aid compression"

Wc2_by_m := (1 – Fraction_x) * (h8_prime – h7)

We1_by_m := Fraction_x * eta_m_e1 * (h3 – he_prime)

We2_by_m := eta_ad_e2 * (h5 – h6)

Wnet_by_m := Wc1_by_m + Wc2_by_m – We1_by_m

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COP := Qa_by_m / Wnet_by_m

COP_i:= T7 / (T2 – T7)

FOM:= COP / COP_i

END

"=="

Now, solve the problem, using the above written EES Procedure:

P1 = 4.053E02 [kPa]

T1 = 270 [K]

P2 = 40.53E02 [kPa]

T2 = 300 [K]

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P3 = P2

T3 = 200[K]

Fraction_x = 0.30

P5 = P2

P7 = 101.3[kPa]

P8 = P1

eta_co = 0.7 "…effcy of main compressor"

eta_ad_e1 = 0.85 "…adiab. effcy of expander 1"

eta_m_e1 = 0.95 "…mech. effcy of expander 1"

eta_c = 0.8 "…adiab. effcy of low temp compressor"

eta_ad_e2 = 0.85 "…adiab. effcy of wet expander"

CALL Coldgas_refrig_He(P1, T1, P2, T2, T3, P7, Fraction_x, eta_co, eta_c, eta_ad_e1, eta_m_e1, eta_ad_e2: T7, Qa_by_m, Wc1_by_m, Wc2_by_m,We1_by_m, We2_by_m, Wnet_by_m, COP, COP_i, FOM)

Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

COP = 0.002747	COP_i = 0.01427	$\eta_{ad,e1}$ = 0.85
$\eta_{ad,e2}$ = 0.85	η_c = 0.8	η_{co} = 0.7
$\eta_{m,e1}$ = 0.95	FOM = 0.1925	$Fraction_x$ = 0.3
P1 = 405.3 [kPa]	P2 = 4053 [kPa]	P3 = 4053 [kPa]
P5 = 4053 [kPa]	P7 = 101.3 [kPa]	P8 = 405.3 [kPa]
$Qa_{by,m}$ = 5.243 [kJ/kg]	T1 = 270 [K]	T2 = 300 [K]
T3 = 200 [K]	T7 = 4.222 [K]	$Wc1_{by,m}$ = 2053 [kJ/kg]
$Wc2_{by,m}$ = 9.993 [kJ/kg]	$We1_{by,m}$ = 154.2 [kJ/kg]	$We2_{by,m}$ = 29.21 [kJ/kg]
$Wnet_{by,m}$ = 1909 [kJ/kg]		

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Also:

Local variables in Procedure Coldgas_refrig_He (1 call, 0.05 sec)

AA =5.212	COP=0.002747	COP_i =0.01427	$\eta_{ad,e1}$=0.85
$\eta_{ad,e2}$=0.85	η_c=0.8	η_{co}=0.7	$\eta_{m,e1}$ =0.95
FOM=0.1925	$Fraction_x$ =0.3	h1=-144.9 [kJ/kg]	h2=22.7 [kJ/kg]
h3=-496.5 [kJ/kg]	h5=-1511 [kJ/kg]	h6=-1545 [kJ/kg]	$h6_{prime}$ =-1540 [kJ/kg]
h7=-1533 [kJ/kg]	h8=-1521 [kJ/kg]	$h8_{prime}$ =-1519 [kJ/kg]	he=-1133 [kJ/kg]
he_{prime} =-1038 [kJ/kg]	hf =-1554 [kJ/kg]	hg=-1533 [kJ/kg]	P1 =405.3 [kPa]
P2 =4053 [kPa]	P3 =4053 [kPa]	P5 =4053 [kPa]	P7 =101.3 [kPa]
P8 =405.3 [kPa]	$Qa_{by,m}$=5.243 [kJ/kg]	s1=-3.394 [kJ/kg-K]	s2=-7.625 [kJ/kg-K]
s3=-9.731 [kJ/kg-K]	s5=-26.07 [kJ/kg-K]	s7=-23.08 [kJ/kg-K]	s8=-23.08 [kJ/kg-K]
se=-9.731 [kJ/kg-K]	sf =-27.98 [kJ/kg-K]	sg=-23.08 [kJ/kg-K]	T1 =270 [K]
T2 =300 [K]	T3 =200 [K]	T7 =4.222 [K]	$Wc1_{by,m}$=2053 [kJ/kg]
$Wc2_{by,m}$=9.993 [kJ/kg]	$We1_{by,m}$=154.2 [kJ/kg]	$We2_{by,m}$=29.21 [kJ/kg]	$Wnet_{by,m}$ =1909 [kJ/kg]
x6=0.6102			

Thus:

COP = 0.002747 … Ans.

FOM = 0.1925 … Ans.

Also, Plot Refrig. effect, COP and FOM as P2 varies from 35 to 60 bar for expander flow rate ratios of 0.3, other factors remaining the same:

First, compute the Parametric Table:

1..6	1 P2 [kPa]	2 $Qa_{by,m}$ [kJ/kg]	3 COP	4 FOM
Run 1	3500	1.983	0.001113	0.07795
Run 2	4000	4.946	0.002607	0.1827
Run 3	4500	7.662	0.003833	0.2685
Run 4	5000	10.29	0.004921	0.3448
Run 5	5500	13.03	0.005996	0.4201
Run 6	6000	16.55	0.007355	0.5153

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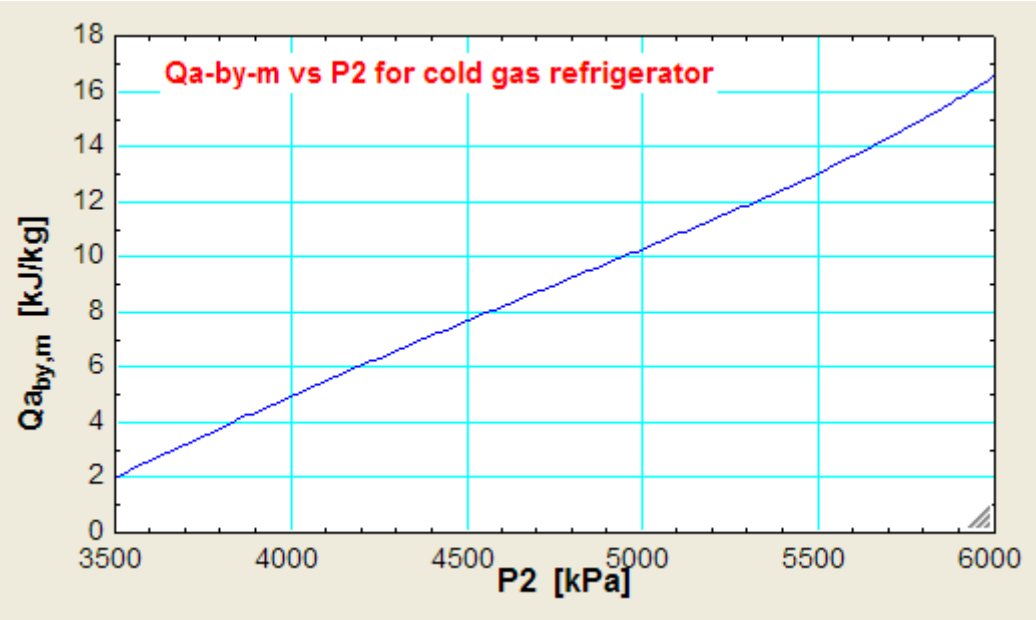
Now, plot the results:



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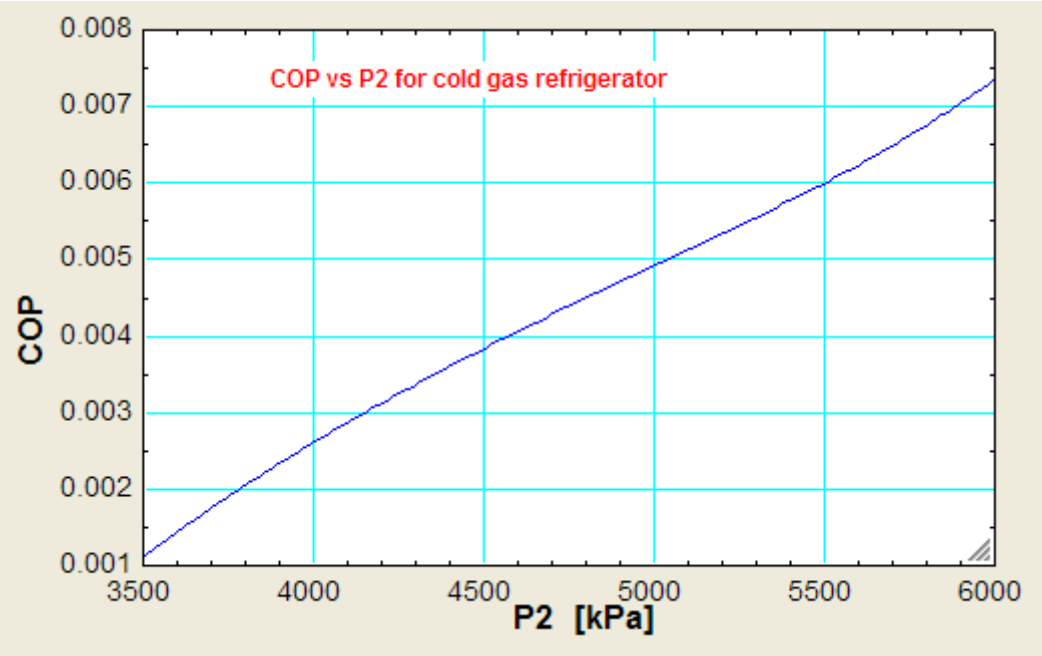

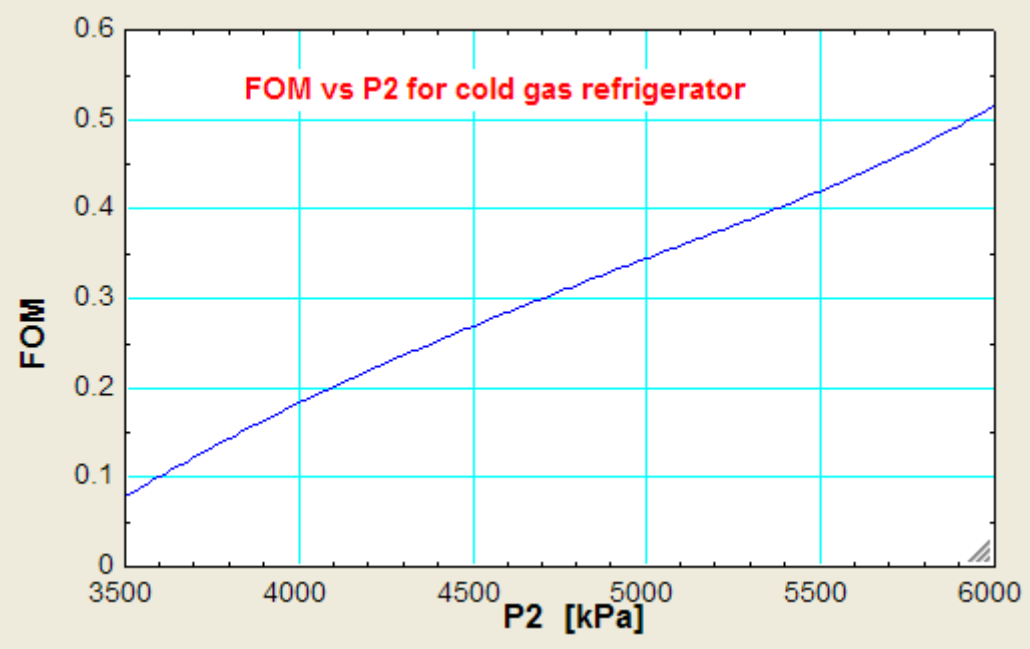

Prob.4.3.16 Determine the fraction of the ideal refrigeration effect (Δ Q/Q_ideal) that is lost in a Philips refrigerator having a regenerator which is 98% efficient. Hydrogen gas is the working substance (cp/cv = 1.4), and the volume ratio (v4/v3) is 1.85. The refrigerator operates between the temp limits of 300 K and 80 K. [1]

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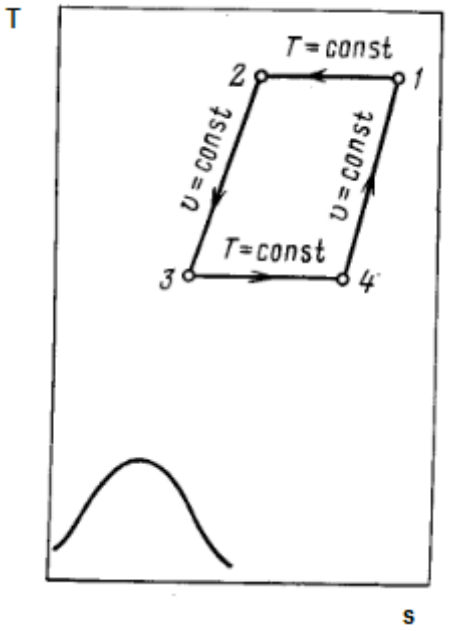

EES Solution:

"Data:"

epsilon = 0.98

gamma = 1.4

T2 = 300 [K]

T3 = 80 [K]

v4_by_v3 = 1.85

"Then, we have:"

"Fraction = DELTA_Q / QA_ideal"

Fraction = ((1 – epsilon) / (gamma – 1)) * (T2 / T3 – 1) / ln(v4_by_v3)

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Results:

Unit Settings: [kJ]/[K]/[kPa]/[kg]/[degrees]

$\varepsilon = 0.98$	Fraction = 0.2235	$\gamma = 1.4$
T2 = 300 [K]	T3 = 80 [K]	$v4_{by,v3} = 1.85$

Thus: Fraction of refrigeration lost due to regenerator inefficiency = 0.2235 = 22.35% … Ans.

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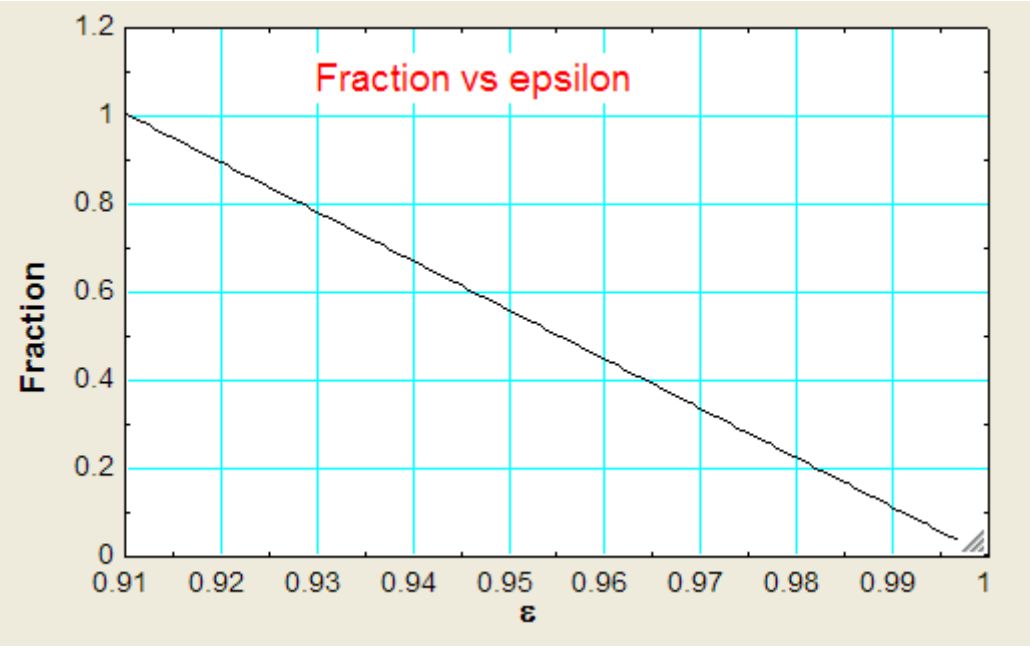
Plot Fraction as epsilon varies from 0.91 to 1:

First, compute the Parametric Table:

1..10	1 ε	2 Fraction
Run 1	0.91	1.006
Run 2	0.92	0.894
Run 3	0.93	0.7823
Run 4	0.94	0.6705
Run 5	0.95	0.5588
Run 6	0.96	0.447
Run 7	0.97	0.3353
Run 8	0.98	0.2235
Run 9	0.99	0.1118
Run 10	1	0

Now, plot:



Prob. 4.3.17 Based on Schmidt's theory for analysis of Stirling cycle (Alpha type), write an EES Program to plot the P-v diagram and also to calculate other performance parameters with air as the working fluid, under following conditions [19]:

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Swept volume of an expansion piston: 0.628 cm3, swept volume of a compression piston: 0.628 cm3, dead volume of the expansion space: 0.2cm3, dead volume of the compression space: 0.2cm3, regenerator volume: 0.2cm3, phase angle: 90deg, mean pressure: 101.3 kPa, expansion gas temperature: 400 deg C, compression gas temperature: 30 deg C, engine speed: 2000 rpm.

Alpha type Stirling engine:

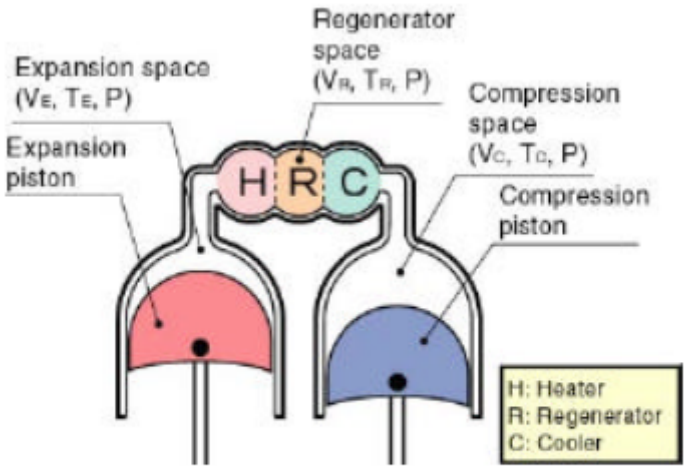

Fig. Alpha-type Stirling Engine

In the program given below:

Inputs: x (crank angle, deg.), dx (phase angle = 90 deg.), TC (comprn. space gas temp, K), TE(expn. space gas temp, K), VSE (swept vol. of expn. piston or displacer, m^3), VSc (swept vol. of comprn. piston or power piston, m^3), VDE (dead vol of expn. space, m^3), VDC(dead vol of comprn. space, m^3), VR(regenerator volume, m^3), N (rpm), Rgas (gas constant, J/kg.K), Pmean (mean pressure, kPa).

Outputs: x (crank angle, deg.), P (engine pressure, kPa), V (total momental volume, m^3),

VE(expn. space momental vol, m^3), VC (comprn. space momental vol, m^3), LE (indicated expn power, kW), LC (indicated comprn power, kW), Li (indicated power, kW), m (total mass of working gas, kg).

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EES Program:

"Data:"
V_SE=0.628E-06[m3]"… swept vol. of expn. space"

V_SC=0.628E-06[m3]"… swept vol. of comprn. space"

V_DE=0.2E-06[m3]"… dead vol. of expn. space"

V_DC=0.2E-06[m3]"…. dead vol. of comprn. space"

V_R=0.2E-06[m3]"… Regenerator Volume"

{x=0[deg]"deg, crank angle"}

dx=90[deg]"deg, phase angle"

P_mean=101.3[kPa]"kPa, mean pressure"

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T_E=400+273[K]"K, expn. space temp."

T_C=30+273[K]"K, comprn. space temp."

N=2000"RPM, Engine speed"

R=0.287[kJ/kg-K]"kJ/kg.K, … Gas const. for air"

"----------"

t=T_C/T_E"temp. ratio"

vratio=V_SC/V_SE"swept vol. ratio"

T_R=(T_E+T_C)/2 [K]"K, Regen. temp."

"Vol. ratios:"

X_DE=V_DE/V_SE"dead vol. ratio of expn. space"

X_DC=V_DC/V_SE"dead vol. ratio of comprn. space"

X_R=V_R/V_SE"dead vol. ratio of regen. space"

"coefficients:"

a=arctan((vratio*sin(dx))/(t+cos(dx)))

S=t+2*t*X_DE+(4*t*X_R)/(1+t)+vratio+2*X_DC

B=sqrt((t^2+2*t*vratio*cos(dx)+vratio^2))

c=B/S

"Instantaneous Engine Pressure:"

P=(P_mean*sqrt(1-c^2))/(1-c*cos(x-a)) "kPa"

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"Instantaneous volumes:"

V_E=(V_SE/2)*(1-cos(x))+V_DE "m3 …for expn. vol."

V_C=(V_SC/2)*(1-cos(x-dx))+V_DC"m3…for comprn. vol."

V=V_E+V_R+V_C"m3….total instantaneous vol."

"mass flow:"

m=(P*V_SE)/(2*R*T_C)*(S-B*cos(x-a))"kg"

P_min=P_mean*sqrt((1-c)/(1+c))"kPa… min. pressure"

P_max=P_mean*sqrt((1+c)/(1-c))"kPa.. max. pressure"

"Indicated expn. work:"

W_E=(P_mean*V_SE*pi*c*sin(a))/(1+sqrt(1-c^2))"kJ"

"Indicated comprn. work:"

W_C=-(P_mean*V_SE*pi*c*t*sin(a))/(1+sqrt(1-c^2))"kJ"

"Indicated work per cycle"

W_i=W_E+W_C"[kJ/cycle]"

"Indicated expn. power:"

L_E=W_E*N/60"kW…heat to be supplied from heat source"

"Indicated comprn. power:"

L_C=W_C*N/60"kW…heat to be rejected in cooler"

"Indicated Power of the engine:"

L_i=W_i*N/60"kW….indicated power of engine"

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"Cycle effcy.:"

eta=W_i/W_e

"Carnot effcy.:"

eta_carnot=1-T_C/T_E

"==="

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Results:

Variation of various parameters as the crank angle x varies from 0 to 360 deg. Is shown below in the Parametric Table:

x [deg]	P [kPa]	V [m³]	V_E [m³]	V_C [m³]
0	111.1	9.140E-07	2.000E-07	5.140E-07
2	112.8	9.032E-07	2.002E-07	5.030E-07
4	114.5	8.929E-07	2.008E-07	4.921E-07
6	116.2	8.829E-07	2.017E-07	4.812E-07
8	117.9	8.734E-07	2.031E-07	4.703E-07
10	119.7	8.642E-07	2.048E-07	4.595E-07
12	121.4	8.556E-07	2.069E-07	4.487E-07
14	123.2	8.474E-07	2.093E-07	4.380E-07
16	125	8.396E-07	2.122E-07	4.274E-07
18	126.8	8.323E-07	2.154E-07	4.170E-07
20	128.5	8.255E-07	2.189E-07	4.066E-07
22	130.3	8.192E-07	2.229E-07	3.964E-07
24	132	8.134E-07	2.271E-07	3.863E-07
26	133.7	8.081E-07	2.318E-07	3.764E-07
28	135.4	8.033E-07	2.368E-07	3.666E-07
30	137.1	7.991E-07	2.421E-07	3.570E-07
32	138.7	7.953E-07	2.477E-07	3.476E-07
34	140.2	7.921E-07	2.537E-07	3.384E-07
36	141.7	7.894E-07	2.600E-07	3.294E-07
38	143.2	7.872E-07	2.666E-07	3.207E-07
40	144.6	7.856E-07	2.735E-07	3.122E-07
42	145.9	7.845E-07	2.807E-07	3.039E-07
44	147.1	7.840E-07	2.881E-07	2.959E-07
46	148.3	7.840E-07	2.959E-07	2.881E-07
48	149.3	7.845E-07	3.039E-07	2.807E-07
50	150.3	7.856E-07	3.122E-07	2.735E-07
52	151.2	7.872E-07	3.207E-07	2.666E-07
54	151.9	7.894E-07	3.294E-07	2.600E-07
56	152.6	7.921E-07	3.384E-07	2.537E-07
58	153.1	7.953E-07	3.476E-07	2.477E-07

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x [deg]	P [kPa]	V [m³]	V_E [m³]	V_C [m³]	x [deg]	P [kPa]	V [m³]	V_E [m³]	V_C [m³]
60	153.5	7.991E-07	3.570E-07	2.421E-07	110	129.9	0.00000104	6.214E-07	2.189E-07
62	153.8	8.033E-07	3.666E-07	2.368E-07	112	128.1	0.000001054	6.316E-07	2.229E-07
64	154	8.081E-07	3.764E-07	2.318E-07	114	126.3	0.000001069	6.417E-07	2.271E-07
66	154	8.134E-07	3.863E-07	2.271E-07	116	124.6	0.000001083	6.516E-07	2.318E-07
68	153.9	8.192E-07	3.964E-07	2.229E-07	118	122.8	0.000001098	6.614E-07	2.368E-07
70	153.7	8.255E-07	4.066E-07	2.189E-07	120	121	0.000001113	6.710E-07	2.421E-07
72	153.4	8.323E-07	4.170E-07	2.154E-07	122	119.3	0.000001128	6.804E-07	2.477E-07
74	153	8.396E-07	4.274E-07	2.122E-07	124	117.5	0.000001143	6.896E-07	2.537E-07
76	152.4	8.474E-07	4.380E-07	2.093E-07	126	115.8	0.000001159	6.986E-07	2.600E-07
78	151.7	8.556E-07	4.487E-07	2.069E-07	128	114.1	0.000001174	7.073E-07	2.666E-07
80	151	8.642E-07	4.595E-07	2.048E-07	130	112.4	0.000001189	7.158E-07	2.735E-07
82	150.1	8.734E-07	4.703E-07	2.031E-07	132	110.7	0.000001205	7.241E-07	2.807E-07
84	149.1	8.829E-07	4.812E-07	2.017E-07	134	109	0.00000122	7.321E-07	2.881E-07
86	148	8.929E-07	4.921E-07	2.008E-07	136	107.4	0.000001236	7.399E-07	2.959E-07
88	146.8	9.032E-07	5.030E-07	2.002E-07	138	105.8	0.000001251	7.473E-07	3.039E-07
90	145.6	9.140E-07	5.140E-07	2.000E-07	140	104.2	0.000001267	7.545E-07	3.122E-07
92	144.3	9.251E-07	5.250E-07	2.002E-07	142	102.7	0.000001282	7.614E-07	3.207E-07
94	142.9	9.367E-07	5.359E-07	2.008E-07	144	101.2	0.000001297	7.680E-07	3.294E-07
96	141.4	9.485E-07	5.468E-07	2.017E-07	146	99.71	0.000001313	7.743E-07	3.384E-07
98	139.9	9.608E-07	5.577E-07	2.031E-07	148	98.27	0.000001328	7.803E-07	3.476E-07
100	138.3	9.733E-07	5.685E-07	2.048E-07	150	96.87	0.000001343	7.859E-07	3.570E-07
102	136.7	9.861E-07	5.793E-07	2.069E-07	152	95.5	0.000001358	7.912E-07	3.666E-07
104	135	9.993E-07	5.900E-07	2.093E-07	154	94.17	0.000001373	7.962E-07	3.764E-07
106	133.3	0.000001013	6.006E-07	2.122E-07	156	92.87	0.000001387	8.009E-07	3.863E-07
108	131.6	0.000001026	6.110E-07	2.154E-07	158	91.6	0.000001402	8.051E-07	3.964E-07

x [deg]	P [kPa]	V [m³]	V_E [m³]	V_C [m³]	x [deg]	P [kPa]	V [m³]	V_E [m³]	V_C [m³]
160	90.37	0.000001416	8.091E-07	4.066E-07	210	70.4	0.000001657	7.859E-07	6.710E-07
162	89.18	0.00000143	8.126E-07	4.170E-07	212	69.98	0.000001661	7.803E-07	6.804E-07
164	88.02	0.000001443	8.158E-07	4.274E-07	214	69.59	0.000001664	7.743E-07	6.896E-07
166	86.9	0.000001457	8.187E-07	4.380E-07	216	69.22	0.000001667	7.680E-07	6.986E-07
168	85.82	0.00000147	8.211E-07	4.487E-07	218	68.88	0.000001669	7.614E-07	7.073E-07
170	84.76	0.000001483	8.232E-07	4.595E-07	220	68.57	0.00000167	7.545E-07	7.158E-07
172	83.75	0.000001495	8.249E-07	4.703E-07	222	68.27	0.000001671	7.473E-07	7.241E-07
174	82.76	0.000001507	8.263E-07	4.812E-07	224	68.01	0.000001672	7.399E-07	7.321E-07
176	81.81	0.000001519	8.272E-07	4.921E-07	226	67.76	0.000001672	7.321E-07	7.399E-07
178	80.9	0.000001531	8.278E-07	5.030E-07	228	67.55	0.000001671	7.241E-07	7.473E-07
180	80.01	0.000001542	8.280E-07	5.140E-07	230	67.35	0.00000167	7.158E-07	7.545E-07
182	79.16	0.000001553	8.278E-07	5.250E-07	232	67.18	0.000001669	7.073E-07	7.614E-07
184	78.34	0.000001563	8.272E-07	5.359E-07	234	67.03	0.000001667	6.986E-07	7.680E-07
186	77.55	0.000001573	8.263E-07	5.468E-07	236	66.91	0.000001664	6.896E-07	7.743E-07
188	76.8	0.000001583	8.249E-07	5.577E-07	238	66.81	0.000001661	6.804E-07	7.803E-07
190	76.07	0.000001592	8.232E-07	5.685E-07	240	66.73	0.000001657	6.710E-07	7.859E-07
192	75.37	0.0000016	8.211E-07	5.793E-07	242	66.67	0.000001653	6.614E-07	7.912E-07
194	74.71	0.000001609	8.187E-07	5.900E-07	244	66.64	0.000001648	6.516E-07	7.962E-07
196	74.07	0.000001616	8.158E-07	6.006E-07	246	66.63	0.000001643	6.417E-07	8.009E-07
198	73.46	0.000001624	8.126E-07	6.110E-07	248	66.65	0.000001637	6.316E-07	8.051E-07
200	72.88	0.00000163	8.091E-07	6.214E-07	250	66.68	0.00000163	6.214E-07	8.091E-07
202	72.33	0.000001637	8.051E-07	6.316E-07	252	66.74	0.000001624	6.110E-07	8.126E-07
204	71.81	0.000001643	8.009E-07	6.417E-07	254	66.83	0.000001616	6.006E-07	8.158E-07
206	71.31	0.000001648	7.962E-07	6.516E-07	256	66.93	0.000001609	5.900E-07	8.187E-07
208	70.84	0.000001653	7.912E-07	6.614E-07	258	67.06	0.0000016	5.793E-07	8.211E-07

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x [deg]	P [kPa]	V [m³]	V_E [m³]	V_C [m³]	x [deg]	P [kPa]	V [m³]	V_E [m³]	V_C [m³]
260	67.22	0.000001592	5.685E-07	8.232E-07	310	79.36	0.000001267	3.122E-07	7.545E-07
262	67.4	0.000001583	5.577E-07	8.249E-07	312	80.22	0.000001251	3.039E-07	7.473E-07
264	67.6	0.000001573	5.468E-07	8.263E-07	314	81.11	0.000001236	2.959E-07	7.399E-07
266	67.82	0.000001563	5.359E-07	8.272E-07	316	82.04	0.00000122	2.881E-07	7.321E-07
268	68.07	0.000001553	5.250E-07	8.278E-07	318	82.99	0.000001205	2.807E-07	7.241E-07
270	68.34	0.000001542	5.140E-07	8.280E-07	320	83.98	0.000001189	2.735E-07	7.158E-07
272	68.64	0.000001531	5.030E-07	8.278E-07	322	85.01	0.000001174	2.666E-07	7.073E-07
274	68.96	0.000001519	4.921E-07	8.272E-07	324	86.07	0.000001159	2.600E-07	6.986E-07
276	69.31	0.000001507	4.812E-07	8.263E-07	326	87.17	0.000001143	2.537E-07	6.896E-07
278	69.68	0.000001495	4.703E-07	8.249E-07	328	88.3	0.000001128	2.477E-07	6.804E-07
280	70.08	0.000001483	4.595E-07	8.232E-07	330	89.46	0.000001113	2.421E-07	6.710E-07
282	70.5	0.00000147	4.487E-07	8.211E-07	332	90.66	0.000001098	2.368E-07	6.614E-07
284	70.95	0.000001457	4.380E-07	8.187E-07	334	91.9	0.000001083	2.318E-07	6.516E-07
286	71.43	0.000001443	4.274E-07	8.158E-07	336	93.17	0.000001069	2.271E-07	6.417E-07
288	71.93	0.00000143	4.170E-07	8.126E-07	338	94.48	0.000001054	2.229E-07	6.316E-07
290	72.46	0.000001416	4.066E-07	8.091E-07	340	95.82	0.00000104	2.189E-07	6.214E-07
292	73.02	0.000001402	3.964E-07	8.051E-07	342	97.2	0.000001026	2.154E-07	6.110E-07
294	73.61	0.000001387	3.863E-07	8.009E-07	344	98.61	0.000001013	2.122E-07	6.006E-07
296	74.22	0.000001373	3.764E-07	7.962E-07	346	100.1	9.993E-07	2.093E-07	5.900E-07
298	74.86	0.000001358	3.666E-07	7.912E-07	348	101.5	9.861E-07	2.069E-07	5.793E-07
300	75.54	0.000001343	3.570E-07	7.859E-07	350	103.1	9.733E-07	2.048E-07	5.685E-07
302	76.24	0.000001328	3.476E-07	7.803E-07	352	104.6	9.608E-07	2.031E-07	5.577E-07
304	76.97	0.000001313	3.384E-07	7.743E-07	354	106.2	9.485E-07	2.017E-07	5.468E-07
306	77.74	0.000001297	3.294E-07	7.680E-07	356	107.8	9.367E-07	2.008E-07	5.359E-07
308	78.53	0.000001282	3.207E-07	7.614E-07	358	109.4	9.251E-07	2.002E-07	5.250E-07
310	79.36	0.000001267	3.122E-07	7.545E-07	360	111.1	9.140E-07	2.000E-07	5.140E-07

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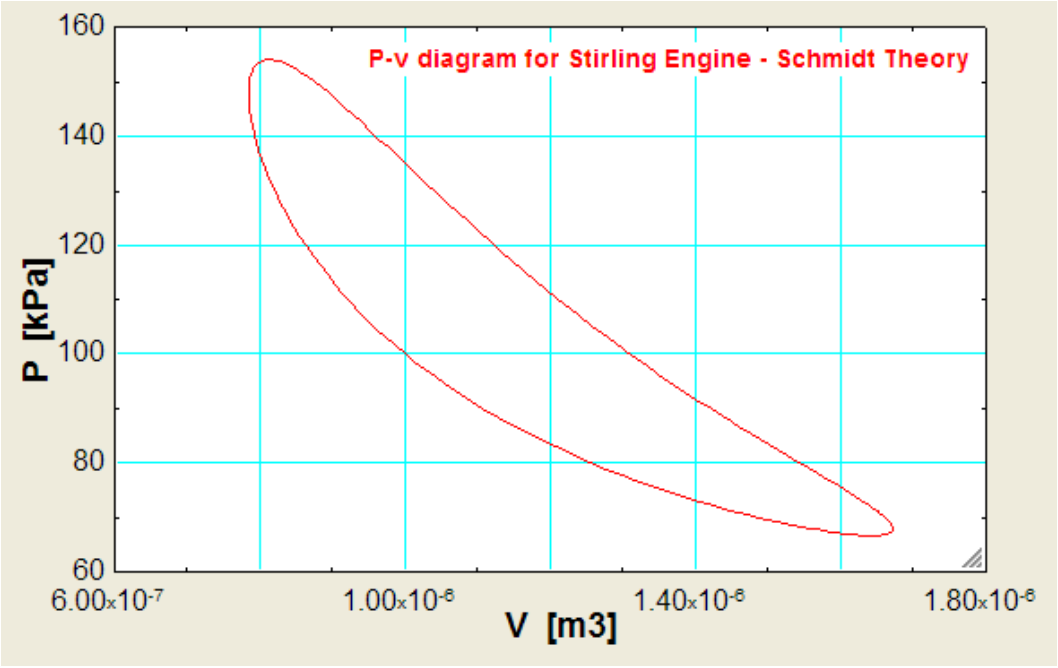

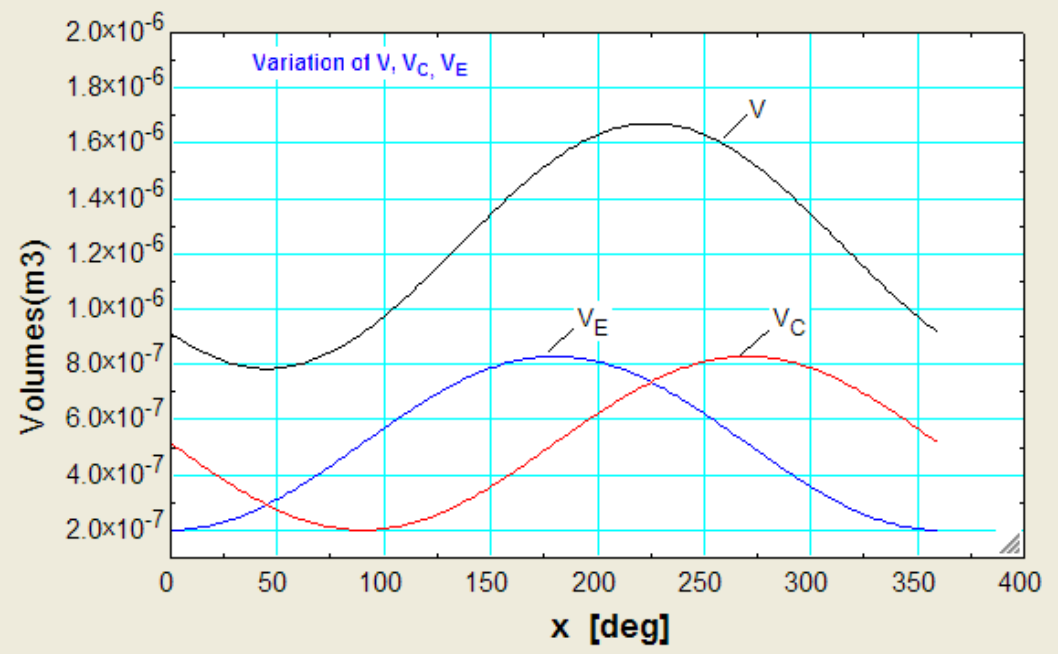

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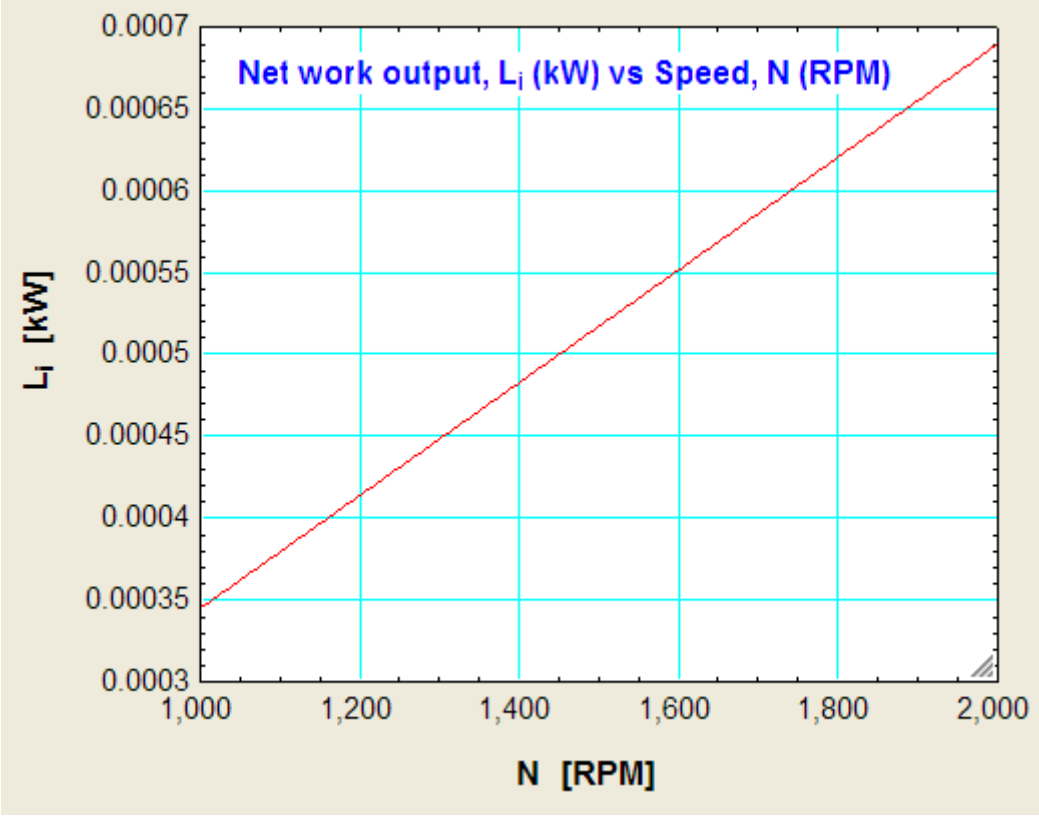
Plot L_i, the net work (kW) as Speed, N varies from 1000 to 2000 RPM:

The Parametric Table:

1..11	1 N [RPM]	2 L_i [kW]
Run 1	1,000	0.0003447
Run 2	1,100	0.0003792
Run 3	1,200	0.0004137
Run 4	1,300	0.0004481
Run 5	1,400	0.0004826
Run 6	1,500	0.0005171
Run 7	1,600	0.0005515
Run 8	1,700	0.000586
Run 9	1,800	0.0006205
Run 10	1,900	0.000655
Run 11	2,000	0.0006894

Now, plot:



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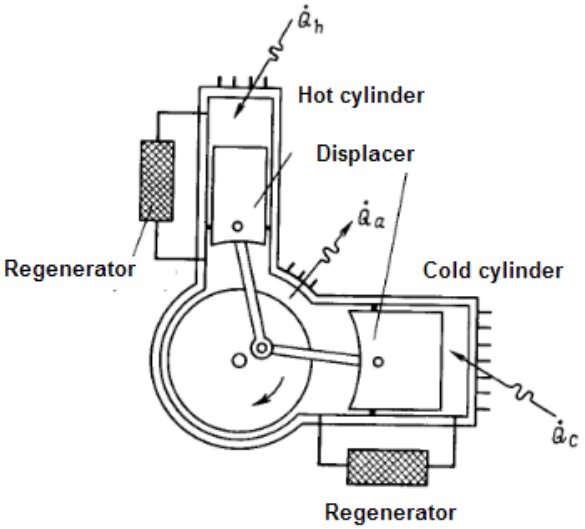
Prob. 4.3.18 An ideal Vuilleumier refrigerator absorbs energy as heat from a high temp source at 600 K and rejects heat to a sink at 300 K. The refrigerator absorbs heat from the low temp region at 20 K. If the heat transfer rate at the hot end of the refrigerator is 2 kW, determine the refrigeration rate at the cold end. [1]



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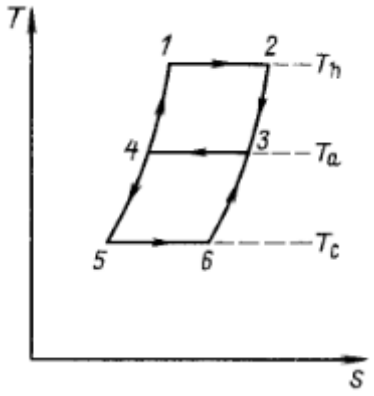

EES Solution:

"Data:"

Th = 600 [K]

Ta = 300 [K]

Tc = 20 [K]

Qh = 2 [kW]

COP = Qc / Qh "..finds Qc (kW)"

COP = (Tc / Th) * ((Th – Ta) / (Ta – Tc)) "…finds COP"

Results:

Unit Settings: SI K kPa kJ mass deg

COP = 0.03571 Qc = 0.07143 [kW] Qh = 2 [kW] Ta = 300 [K] Tc = 20 [K]

Th = 600 [K]

Thus:

COP = 0.03571 … Ans.

Qc = 0.07143 kW … Ans.

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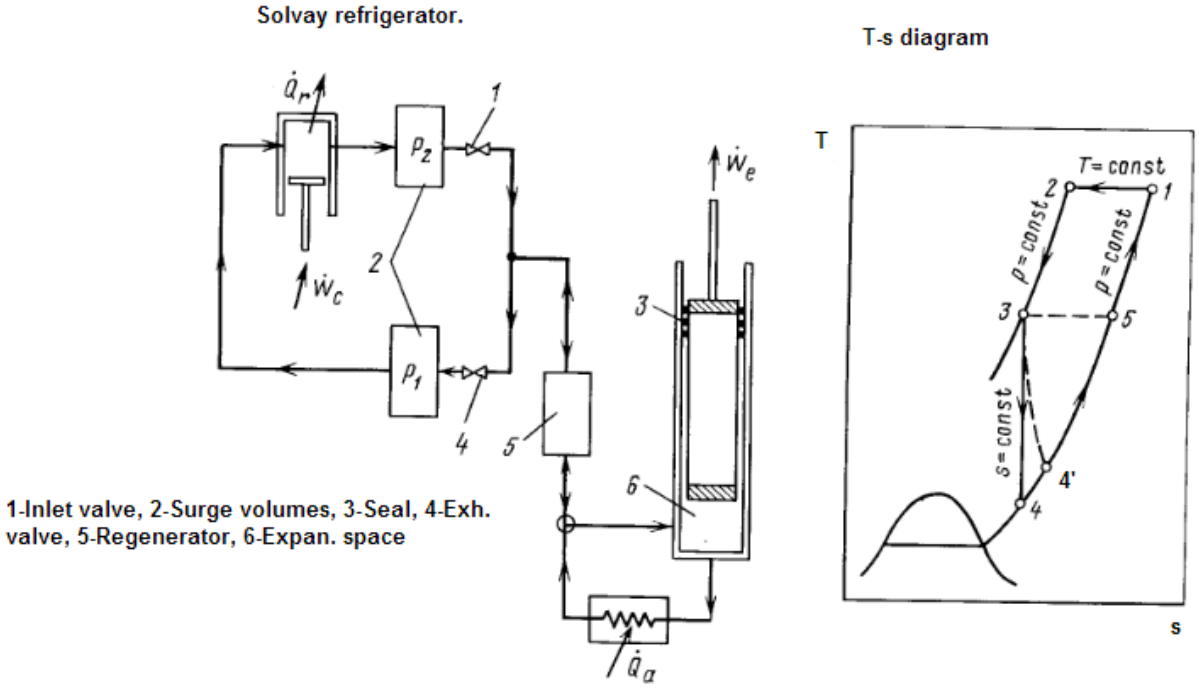
Prob.4.3.19 A Solvay refrigerator uses neon as the working fluid, with the expander work utilized to aid in compression. Neon is compressed from 152 kPa to 1.013 MPa and 294 K in a compressor having an overall isothermal effcy of 75%. The adiabatic effcy of the expander is 90% and the mechanical effcy of expander is 96%. At the beginning of the expansion process, the temp of neon gas is 85.6 K and the pressure is 1.013 MPa. The neon gas enters the regenerator at the cold end at 152 kPa and 85.6 K. Determine the COP of the refrigerator. [1]



EES Solution:

"Data:"

"Fluid = Neon"

P1 = 152 [kPa]

P2 = 1.013E03 [kPa]

T1 = 294 [K]

T2 = T1

P3 = P2

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P5 = P1

T3 = 85.6 [K]

T5 = T3

eta_co = 0.75 "…overall effcy of compressor"

eta_ad = 0.9 "… adiab. effcy of expander"

eta_e_m = 0.96 "… mech. effcy of expander"

"Then, we have:"

h1 = Enthalpy(Neon,T=T1,P=P1) "kJ/kg"

s1 = Entropy(Neon,T=T1,P=P1) "kJ/kg-K"

h2 = Enthalpy(Neon,T=T2,P=P2) "kJ/kg"

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s2 = Entropy(Neon,T=T2,P=P2) "kJ/kg-K"

h3 = Enthalpy(Neon,T=T3,P=P3) "kJ/kg"

s3 = Entropy(Neon,T=T3,P=P3) "kJ/kg-K"

s4 = s3 "… for isentropic expn."

h4 = Enthalpy(Neon,P=P1,s=s4) "kJ/kg"

h5 = Enthalpy(Neon,T=T5,P=P5) "kJ/kg"

"Refrigeration effect:"

h4_prime = h3 – eta_ad * (h3 – h4)

Qa_by_m = h5 – h4_prime

"Net compressor work:"

Wnet_by_m = ((T2 * (s1 – s2) – (h1 – h2)) / eta_co) – eta_e_m * eta_ad * (h3 – h4)

COP = Qa_by_m / Wnet_by_m

"=="

Results:

Unit Settings: SI K kPa kJ mass deg

COP = 0.1616	η_{ad} = 0.9	η_{co} = 0.75
$\eta_{e,m}$ = 0.96	h1 = -4.217 [kJ/kg]	h2 = -3.958 [kJ/kg]
h3 = -221.2 [kJ/kg]	h4 = -267.1 [kJ/kg]	h4' = -262.5 [kJ/kg]
h5 = -219.3 [kJ/kg]	P1 = 152 [kPa]	P2 = 1,013 [kPa]
P3 = 1,013 [kPa]	P5 = 152 [kPa]	$Qa_{by,m}$ = 43.2 [kJ/kg]
s1 = -0.1817 [kJ/kg-K]	s2 = -0.964 [kJ/kg-K]	s3 = -2.255 [kJ/kg-K]
s4 = -2.255 [kJ/kg-K]	T1 = 294 [K]	T2 = 294 [K]
T3 = 85.6 [K]	T5 = 85.6 [K]	$Wnet_{by,m}$ = 267.4 [kJ/kg]

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Thus:

Refrig. effect = Qa_by_m = 43.2 kJ/kg … Ans.

Net compressor work = Wnet_by_m = 267.4 kJ/kg …. Ans.

COP = 0.1616 … Ans.

Plot Refrig. effect and COP as high pressure P2 varies from 5 to 20 bar:

First, compute the Parametric Table:

1..16	P2 [kPa]	$Qa_{by,m}$ [kJ/kg]	$Wnet_{by,m}$ [kJ/kg]	COP
Run 1	500	30.55	164	0.1863
Run 2	600	34.13	190.3	0.1793
Run 3	700	36.98	212.8	0.1738
Run 4	800	39.32	232.4	0.1692
Run 5	900	41.3	249.8	0.1653
Run 6	1,000	43	265.4	0.162
Run 7	1,100	44.49	279.7	0.159
Run 8	1,200	45.81	292.8	0.1565
Run 9	1,300	46.99	304.9	0.1541
Run 10	1,400	48.05	316.1	0.152
Run 11	1,500	49.03	326.6	0.1501
Run 12	1,600	49.92	336.4	0.1484
Run 13	1,700	50.74	345.7	0.1468
Run 14	1,800	51.5	354.5	0.1453
Run 15	1,900	52.21	362.9	0.1439
Run 16	2,000	52.88	370.8	0.1426

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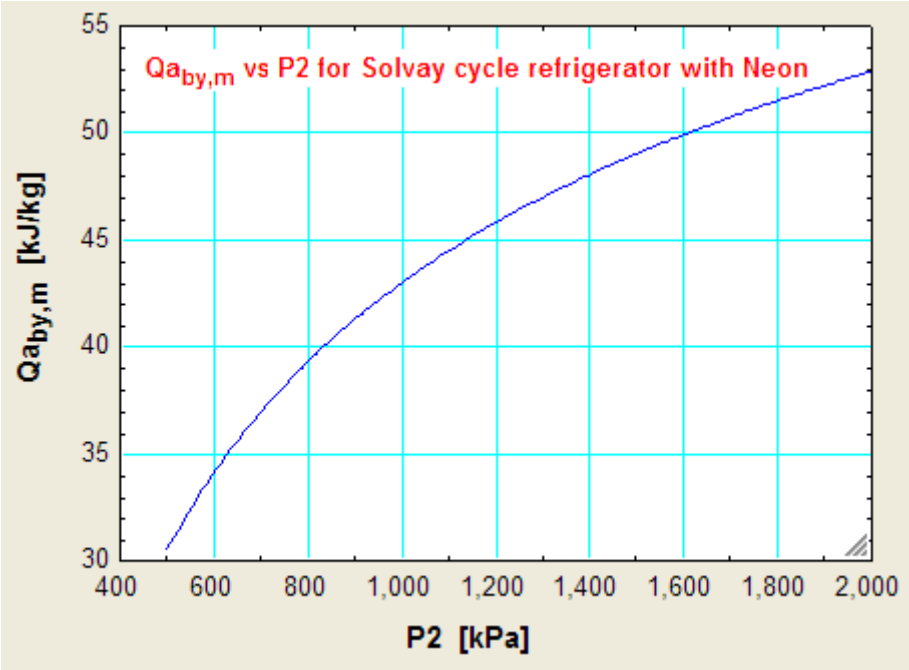
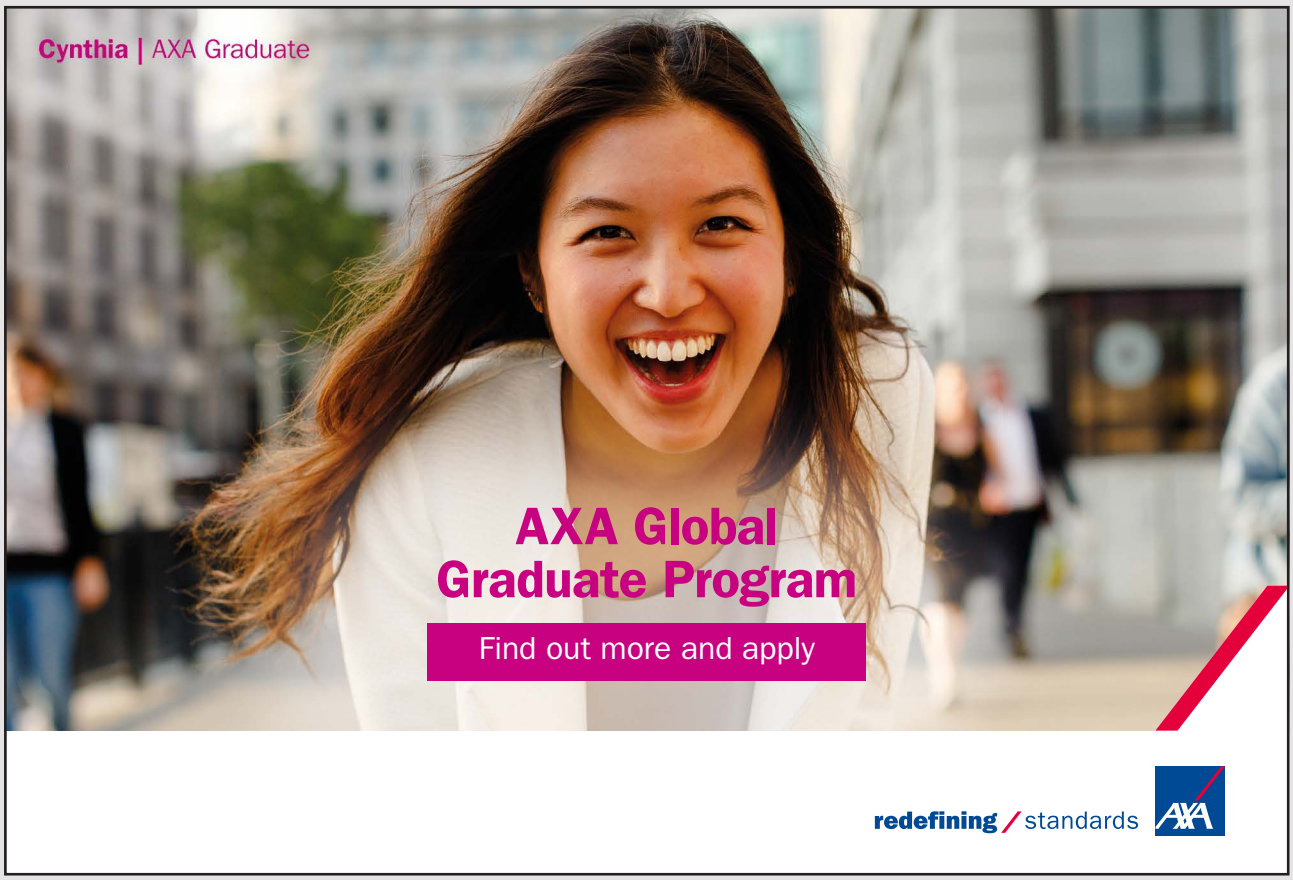
Now, plot:





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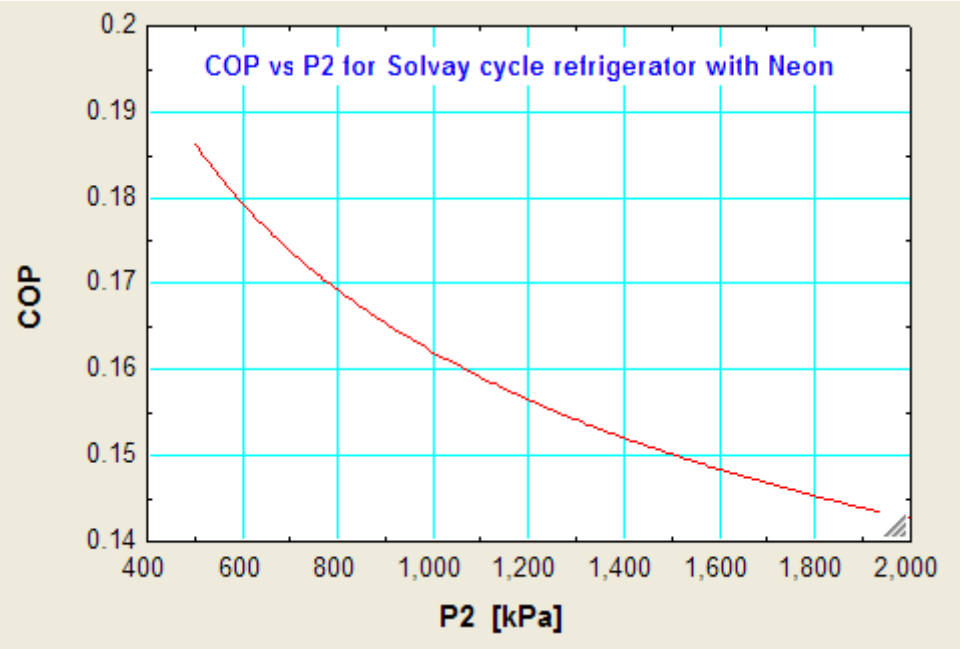

Prob. 4.3.20 Write an EES Procedure to find the various parameters for a Gifford-McMahon (G-M) cycle refrigerator, using a given working gas.

A G-M refrigerator operates between the pressure limits of 1.013 bar and 10.13 bar using helium as working medium. The max. temp in the space to be cooled is 70 K and the temp of the gas leaving the compressor is 300 K. Assume that regenerator efficiency is 100%, compressor overall efficiency = 60%, adiabatic efficiency of expansion in expansion space = 90%. Determine the refrigeration effect, the COP and the FOM for the system. [1]

Also, plot:

a) refrig. effect vs regen. effcy for T5 = 70, 100 and 120 K
b) the effect on COP and FOM by varying regen. effectiveness, for compressor efficiencies of 0.6, 0.8 and 1.

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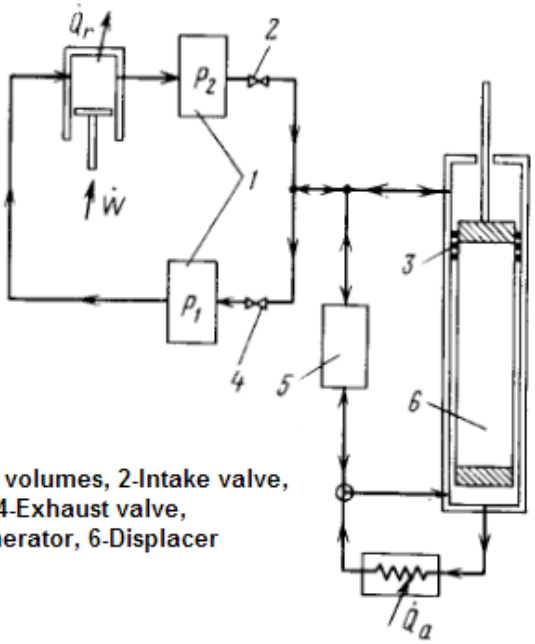
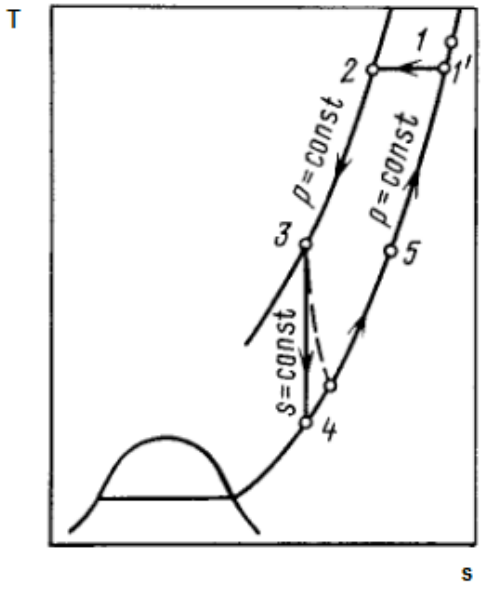
G-M cycle refrigerator.



1-Surge volumes, 2-Intake valve,
3-Seal, 4-Exhaust valve,
5-Regenerator, 6-Displacer

T-s diagram



EES Procedure:

PROCEDURE GM_cycle_refrig(Fluid$, P1, P2, T2, T5, eta_co, eta_ad, epsilon_regen: T1_prime, T3, T4_prime, v3,v4_prime, Qa_by_m, W_by_m, COP, COP_i, FOM)

"Gives various parameters for a GM cycle refrign. system for given working fluid"

"Inputs:
Fluid$, Low and High pressures:P1, P2 (kPa),
T2 = Temp at exit of after cooler of compressor (K),
T5 = refrign. termp. (K),
eta_co = compressor overall effcy,
eta_ad = adiab. effcy of expn. space,
epsilon_regen = regenerator effcy."

"Outputs:
T1_prime = temp of gas exiting the refrigerator
T3 = temp of high pressure gas at the exit of regenerator in to the expansion space
T4_prime = temp of gas after expansion in the expansion space, taking in to account adiabatic effcy of expansion
v3 = sp. vol. at state 3; v4_prime = sp. vol. at state 4_prime

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Qa_by_m = refrig effect per kg gas compressed; W_by_m =work done per kg of gas compressed
COP = coeff of performance; COP_i = ideal COP for refrign at constant pressure
FOM = figure of merit for the cycle"

```
h2:= ENTHALPY(Fluid$, T=T2, P=P2)
s2 := ENTROPY(Fluid$, T=T2, P=P2)

h5:= ENTHALPY(Fluid$, T=T5, P=P1)

T3 := T5

h3:= ENTHALPY(Fluid$, T=T3, P=P2)

s3 := ENTROPY(Fluid$, T=T3, P=P2)

s4 := s3

h4:= ENTHALPY(Fluid$, s=s4, P=P1)
```

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T4 :=Temperature(Fluid$,P=P1,h=h4)

h4_prime := h4 + (1 – eta_ad) * (h3 – h4)

T4_prime :=Temperature(Fluid$,P=P1,h=h4_prime)

v3 := Volume(Fluid$,T=T3,P=P2)

v4_prime := Volume(Fluid$,T=T4_prime,P=P1)

DELTA_Q := (1 – epsilon_regen) * (h2 – h3)

Qa_by_m := (v3 / v4_prime) * (h5 – h4_prime) – DELTA_Q

h1_prime := h2 + Qa_by_m

T1_prime := Temperature(Fluid$,P=P1,h=h1_prime)

h1 := ENTHALPY(Fluid$, T=T2, P=P1)

s1 := ENTROPY(Fluid$, T=T2, P=P1)

W_by_m := (T2 * (s1 – s2) – (h1 – h2)) / eta_co

COP := Qa_by_m / W_by_m

COP_i := (T5 – T4_prime) / (T2 * ln(T5 / T4_prime) – (T5 – T4_prime))

FOM := COP / COP_i

END

"=="

Now, solve the problem:

P1 = 101.3 [kPa]

P2 = 1013 [kPa]

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T2 = 300 [K]

T5 = 70 [K]

eta_co = 0.6

eta_ad = 0.9

epsilon_regen = 1

Fluid$ = 'Helium'

CALL GM_cycle_refrig(Fluid$, P1, P2, T2, T5, eta_co, eta_ad, epsilon_regen : T1_prime, T3, T4_prime, v3,v4_prime, Qa_by_m, W_by_m, COP, COP_i, FOM)

Results:

Unit Settings: SI K kPa kJ mass deg

COP = 0.01824	COP_i = 0.1934	ε_{regen} = 1
η_{ad} = 0.9	η_{co} = 0.6	Fluid$ = 'Helium'
FOM = 0.09429	P1 = 101.3 [kPa]	P2 = 1,013 [kPa]
$Qa_{by,m}$ = 43.7 [kJ/kg]	T1' = 309 [K]	T2 = 300 [K]
T3 = 70 [K]	T4' = 32.12 [K]	T5 = 70 [K]
v3 = 0.1464 [m^3/kg]	v4' = 0.6603 [m^3/kg]	$W_{by,m}$ = 2,396 [kJ/kg]

Thus:

Refrig. effect = Qa_by_m = 43.7 kJ/kg … Ans.

COP = 0.01824 … Ans.

FOM = 0.09429 … Ans.

Also, plot:

a) **refrig. effect vs regen. effcy for T5 = 70, 100 and 120 K**
b) **the effect on COP and FOM by varying regen. effectiveness, for compressor efficiencies of 0.6, 0.8 and 1:**

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a) **refrig. effect vs regen. effcy for T5 = 70, 100 and 120 K:**

Parametric Table:

	T5 = 70 K	100 K	120 K
ε_{regen}	$Qa_{by,m}$ [kJ/kg]	$Qa_{by,m}$ [kJ/kg]	$Qa_{by,m}$ [kJ/kg]
0.97	7.835	30.85	46.2
0.975	13.81	36.04	50.88
0.98	19.79	41.24	55.55
0.985	25.77	46.43	60.23
0.99	31.74	51.63	64.9
0.995	37.72	56.82	69.58
1	43.7	62.02	74.25

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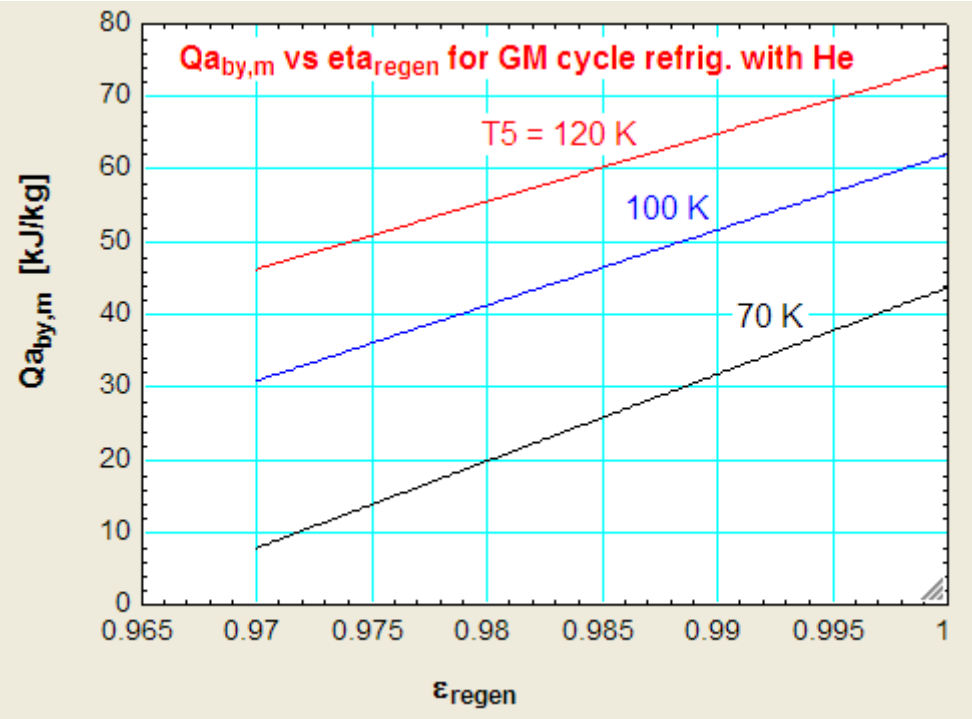

b) **the effect on COP and FOM by varying regen. effectiveness, for compressor efficiencies of 0.6, 0.8 and 1:**

Parametric Table:

	eta_co = 0.6	0.6	0.8	0.8	1	1
1 ε_regen	3 COP	4 FOM	3 COP	4 FOM	3 COP	4 FOM
0.97	0.00327	0.01691	0.004361	0.02254	0.005451	0.02818
0.975	0.005765	0.0298	0.007687	0.03974	0.009609	0.04967
0.98	0.00826	0.0427	0.01101	0.05694	0.01377	0.07117
0.985	0.01075	0.0556	0.01434	0.07413	0.01792	0.09266
0.99	0.01325	0.0685	0.01767	0.09133	0.02208	0.1142
0.995	0.01574	0.08139	0.02099	0.1085	0.02624	0.1357
1	0.01824	0.09429	0.02432	0.1257	0.0304	0.1572

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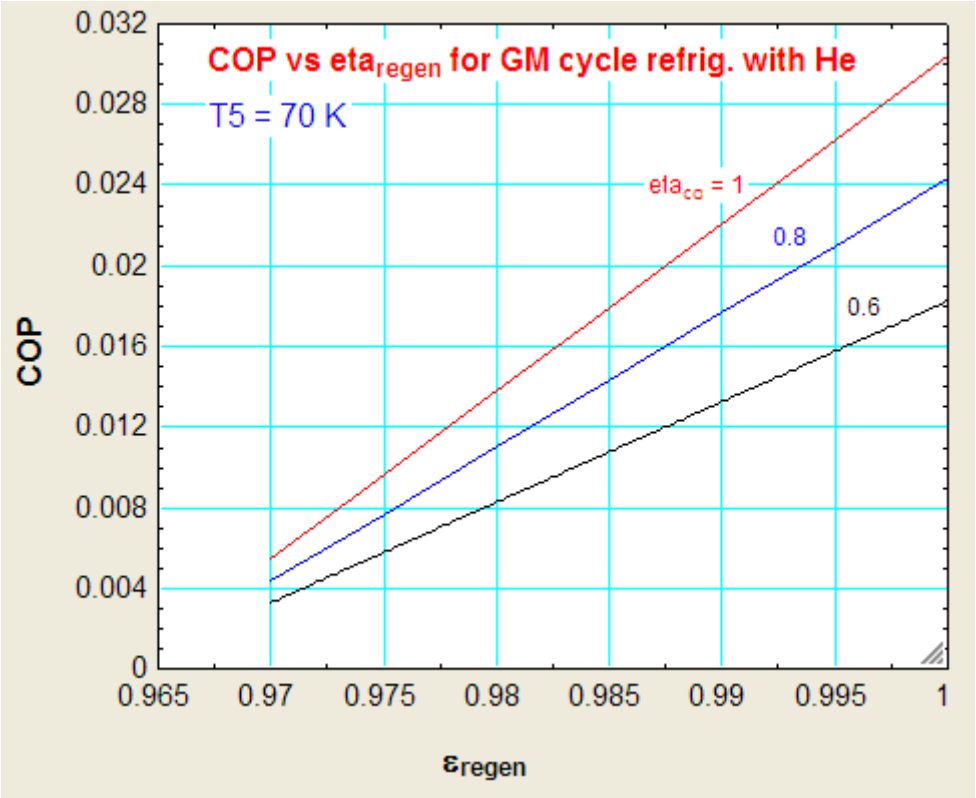
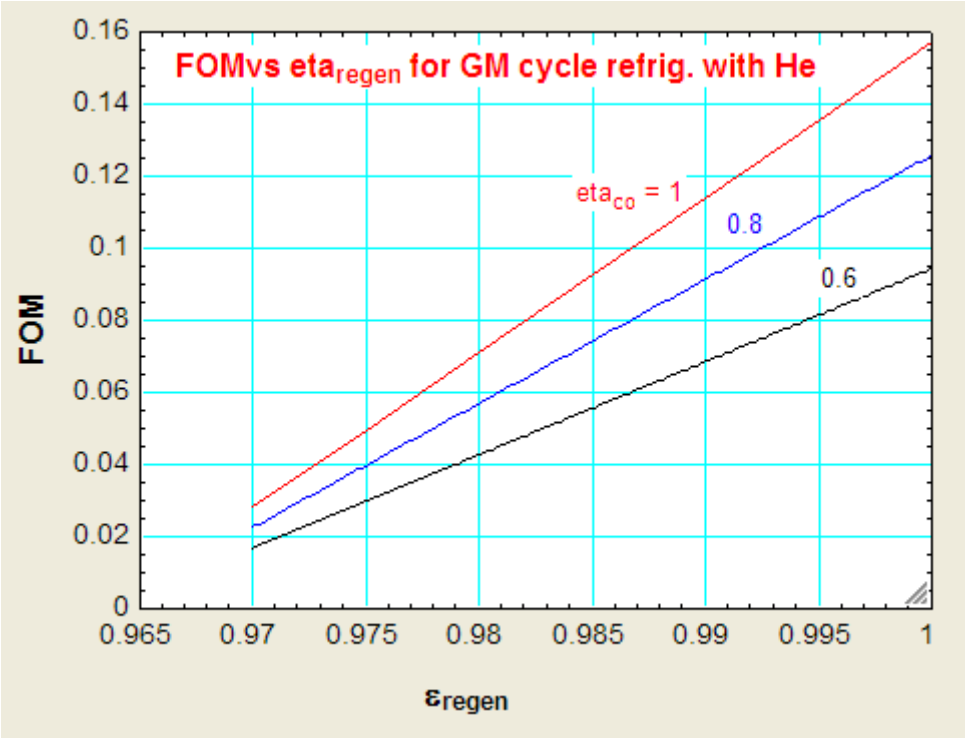
Plot:





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Prob. 4.3.21 Write a EES Procedure to determine the effectiveness of a practical regenerator of a GM cycle refrigerator, consisting of copper wire screen matrix housed in a perspex displacer, when a given fluid is working gas.

Frst, we need the porosity of the regenerator.

This is calculated knowing the physical dimensions of the regenerator and the mass of copper screens.

porosity = (Total vol. - metal vol.)/Total vol.

i.e.

$$p := \frac{\frac{\pi \cdot DR^2}{4} \cdot LR - \frac{m\_cu}{\rho\_cu}}{\frac{\pi \cdot DR^2}{4} \cdot LR}$$

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Now, write the EES Procedure:

PROCEDURE Regen_GM(Fluid$, PH, PL, TH, TL, N, d_i, d_0, l_cyl, d_disp, l_disp, LR, DR, dw, p : Q_ideal, m_fluid, A_ht, Re, h, NTU, I, f, DELTAP, Qloss_reg)

"Gives various parameters for a regenerator of GM cycle refrign. system for given working fluid"

"Inputs:
Fluid$, Low and High pressures:PH, PL (kPa), TH = High Temp (K), , TL = Low termp. (K), d_i = cylinder ID, d_0 = cyl. OD, l_cyl = cyl. length, d_disp = dia of displacer, l_disp = length of displacer, LR = length of regen, DR = dia of regen., dw = wire dia, (m), p = porosity, as defined."

"Outputs:
Q_ideal = ideal refrign., m_fluid = mass flow rate of fluid (kg/s), A_ht = heat transfer area of mesh (m^2), Re = Reynolds No., h = heat transfer coeff.(kW/m^2.K), NTU = No. of Transfer Units, I = regen. ineffcy., f = friction factor., DELTAP = pressure drop (Pa), Qloss_reg = regen. heat loss (kW)"

MW := MolarMass(Fluid$) "…Mol. wt. of fluid"

R_u := 8.314 "kJ/kg-K … universal gas const."

R_fluid := R_u / MW "kJ/kg-K … Particular gas const."

cp_fluid :=Cp(Fluid$,T=TH,P=PH)"kJ/kg-K"

cv_fluid :=Cv(Fluid$,T=TH,P=PH)"kJ/kg-K"

gamma := cp_fluid / cv_fluid "… ratio of sp. heats"

rho_cu := 8874 "kg/m^3 … density of copper"

T_m = (TH + TL) / 2 "mean temp., K"

mu_fluid := Viscosity(Fluid$,T=T_m,P=PL) "… viscosity of fluid, kg/m.s"

A_ht := (4 * (1 – p) / dw) * pi * DR^2 * LR / 4 "… heat transfer area"

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d_eq := 4 * LR * p * pi * DR^2 / (4 * A_ht) "m … Equiv. dia"

V_stroke := (pi * d_i^2 / 4) * (l_cyl – l_disp) "… stroke vol."

m_fluid :=((PH * V_stroke) / (R_fluid * TL)) * (N / 60) "kg/s …. Fluid flow rate "

G := m_fluid / (p * pi * DR^2 / 4)

Re := G * d_eq / mu_fluid"…Reynolds No."

Pr := Prandtl(Fluid$,T=T_m,P=PL) "…Prandtl No."

St := 0.68 * (Re^(-0.407)) * Pr^(-2/3)"… Stanton No."

cp := Cp(Fluid$,T=T_m,P=PL)"kJ/kg-K"

h := St * G * cp "…heat transfer coeff."

NTU := h * A_ht / (2 * cp * m_fluid)

m_s := (pi * DR^2 / 4) * LR * (1 – p) * rho_cu "….mass of solid, i.e. copper"

tau := (1 / (N / 60)) * (1/2) "s… duration of each blow (hot or cold)"

CR := m_s * c_('Copper', T_m) / (cp * m_fluid * tau) "….capacity rate ratio"

DELTAT := m_fluid * (TH – TL) * tau * cp / (m_s * c_('Copper', T_m)) "…. matrix temp swing"

I := 1 / (1 + NTU) "…. Regen. Inefficiency"

Qloss_reg := I * m_fluid * (TH – TL) * cp / 2 "Rgen. Heat loss… factor 2 in the denominator, since loss occurs only during the pressurising period"

f := (860 * (1 – p) / Re) + (2.2 * p / Re^0.1) "… friction factor"

rho_fluid := Density(Fluid$,T=T_m,P=PH) "… density of fluid"

Q_ideal := (PH – PL) * V_stroke * N / 60 "kW …. Ideal refrign. produced"

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DELTAP := (f * LR / d_eq) * (G^2 / (2* rho_fluid)) "….pressure drop"

END

"=="

Prob. 4.3.22 In a practical GM cycle refrigerator using Helium, following are the data. Apply the EES Procedure written above and determine the various parameters of interest.

Data:

PH = 900 kPa; PL = 101.3 kPa; N = 130 RPM; TH = 310 K; TL = 80 K;

d_i = 0.0486 m; d_0 = 0.05 m; l_cyl = 0.24 m; d_disp = 0.0473 m; l_disp = 0.22 m;

LR = 0.101 m; DR = 0.042 m; dw = 8E-05 m; p = 0.749 …porosity.

Fluid$ = 'Helium'

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EES Solution:

Applying the EES Procedure written above:

CALL Regen_GM(Fluid$, PH, PL, TH, TL, N, d_i, d_0, l_cyl, d_disp, l_disp, LR, DR, dw, p : Q_ideal, m_fluid, A_ht, Re, h, NTU, I, f, DELTAP, Qloss_reg)

Results:

Unit Settings: SI K kPa kJ mass deg

A_{ht} = 1.756 [m^2]	ΔP = 564.3 [Pa]	DR = 0.042 [m]
dw = 0.00008 [m]	d_0 = 0.05 [m]	d_{disp} = 0.0473 [m]
d_i = 0.0486 [m]	f = 33.45	Fluid$ = 'Helium'
h = 0.8936 [kW/m^2-K]	I = 0.002873	LR = 0.101 [m]
l_{cyl} = 0.24 [m]	l_{disp} = 0.22 [m]	m_{fluid} = 0.0004354 [kg/s]
N = 130 [RPM]	NTU = 347	p = 0.749
PH = 900 [kPa]	PL = 101.3 [kPa]	$Qloss_{reg}$ = 0.0007471 [kW]
Q_{ideal} = 0.0642 [kW]	Re = 6.728	TH = 310 [K]
TL = 80 [K]		

Thus:

Ideal refrign. = Q_ideal = 0.0642 kW = 64.2 W … Ans.

Overall heat transfer coeff. in regenerator = h = 0.8936 kW/m^2.K = 893.6 W/m^2.K … Ans.

Regen. ineffcy = I = 0.002873 = 0.2873% …. Ans.

Regen. heat loss = Qloss_reg = 0.0007471 kW = 0.7471 W … Ans.

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Other details of calculations:

Local variables in Procedure Regen_GM (1 call, 0.05 sec)

A_{ht} =1.756 [m^2]	cp=5.193 [kJ/kg-K]	cp_{fluid}=5.192 [kJ/kg-K]
cv_{fluid}=3.117 [kJ/kg-K]	ΔP =564.3 [Pa]	ΔT =1.098 [K]
dw =0.00008 [m]	d_0=0.05 [m]	d_{disp}=0.0473 [m]
d_i =0.0486 [m]	f =33.45	Fluid$='Helium'
γ=1.666	h=0.8936 [kW/m^2-K]	I =0.002873
l_{cyl} =0.24 [m]	l_{disp}=0.22 [m]	μ_{fluid}=0.00001489 [kg/m-s]
m_{fluid} =0.0004354 [kg/s]	m_s =0.3117 [kg]	N =130 [RPM]
p=0.749	PH =900 [kPa]	PL =101.3 [kPa]
$Qloss_{reg}$=0.0007471 [kW]	Q_{ideal} =0.0642 [kW]	Re =6.728
ρ_{fluid}=2.207 [kg/m^3]	R_{fluid}=2.077 [kJ/kg-K]	R_u =8.314 [kJ/kgmol-K]
τ=0.2308 [s]	TH =310 [K]	TL =80 [K]
V_{stroke} =0.0000371 [m^3]		

Effect of changing PH:

Parametric Table:

1..14	1 PH [kPa]	2 Q_{ideal} [kW]	3 I	4 $Qloss_{reg}$ [kW]	5 ΔP [Pa]
Run 1	200	0.007934	0.00156	0.00009013	544.4
Run 2	300	0.01597	0.001839	0.0001594	547.4
Run 3	400	0.02401	0.002067	0.0002389	550.3
Run 4	500	0.03205	0.002263	0.0003269	553.2
Run 5	600	0.04009	0.002437	0.0004225	556
Run 6	700	0.04813	0.002595	0.0005247	558.8
Run 7	800	0.05617	0.002739	0.0006331	561.6
Run 8	900	0.0642	0.002873	0.0007471	564.3
Run 9	1,000	0.07224	0.002999	0.0008664	567
Run 10	1,100	0.08028	0.003117	0.0009906	569.7
Run 11	1,200	0.08832	0.003229	0.001119	572.3
Run 12	1,300	0.09636	0.003336	0.001253	575
Run 13	1,400	0.1044	0.003437	0.00139	577.6
Run 14	1,500	0.1124	0.003535	0.001532	580.2

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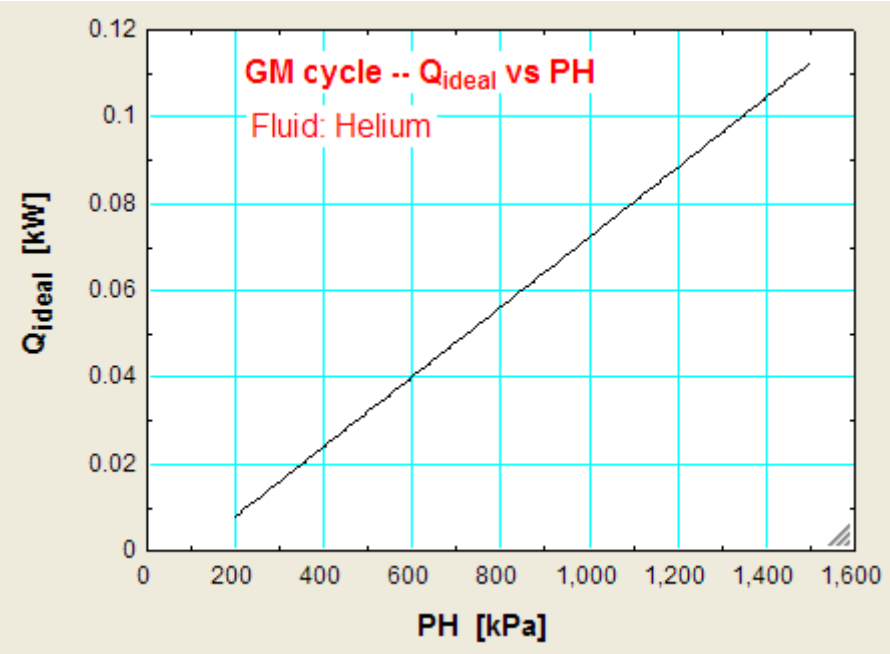
Plots:



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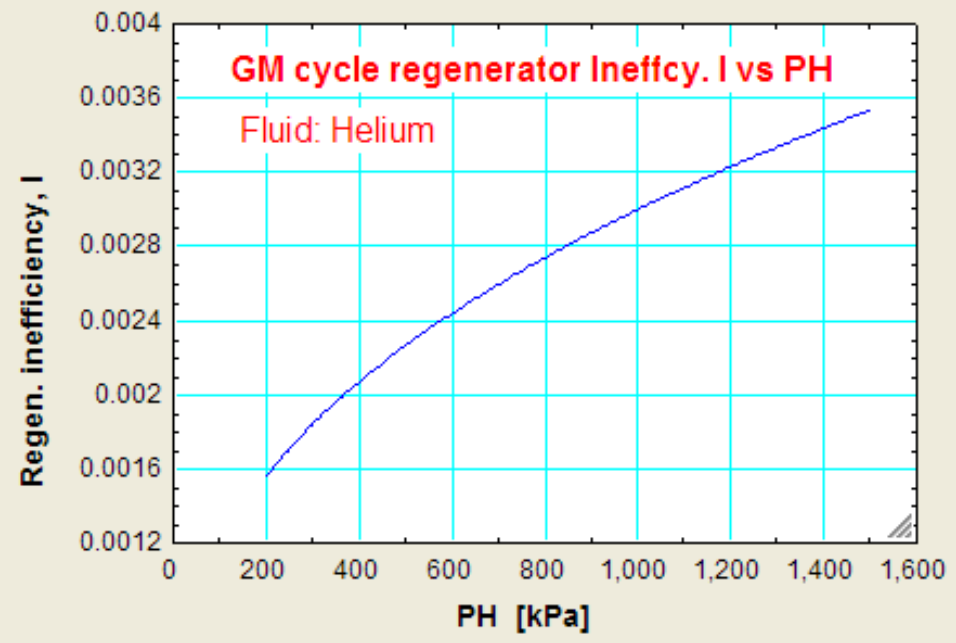

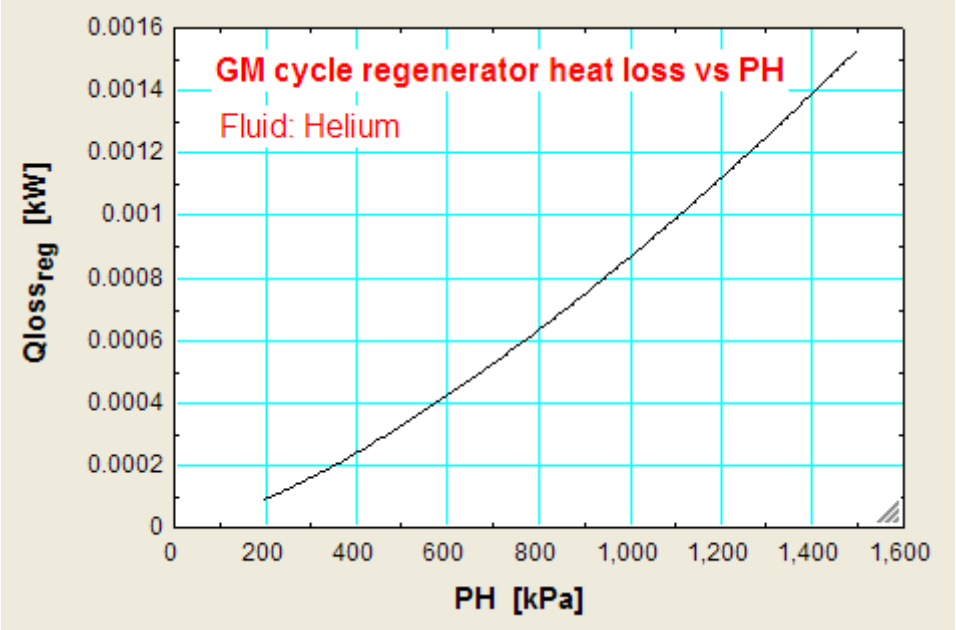

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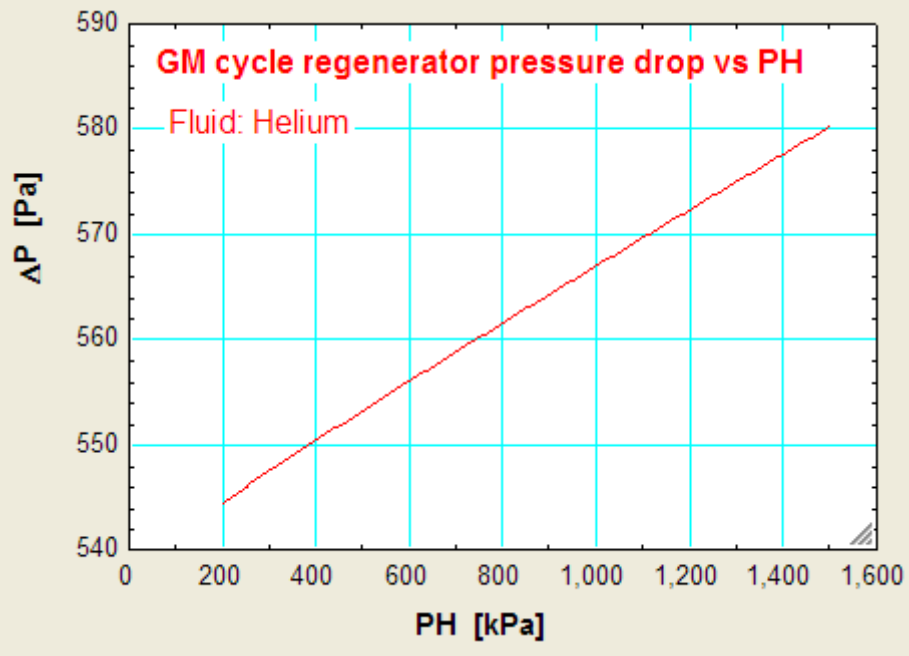

Plot Regen. Ineffcy I vs PH for Speeds N = 130, 100 and 75 RPM:

Parametric Table:

	N = 130 RPM	100 RPM	75 RPM
PH [kPa]	I	I	I
200	0.00156	0.001402	0.001247
300	0.001839	0.001653	0.001471
400	0.002067	0.001858	0.001653
500	0.002263	0.002035	0.00181
600	0.002437	0.002191	0.001949
700	0.002595	0.002332	0.002075
800	0.002739	0.002462	0.002191
900	0.002873	0.002583	0.002298
1,000	0.002999	0.002696	0.002399
1,100	0.003117	0.002802	0.002493
1,200	0.003229	0.002903	0.002583
1,300	0.003336	0.002999	0.002668
1,400	0.003437	0.00309	0.00275
1,500	0.003535	0.003178	0.002828

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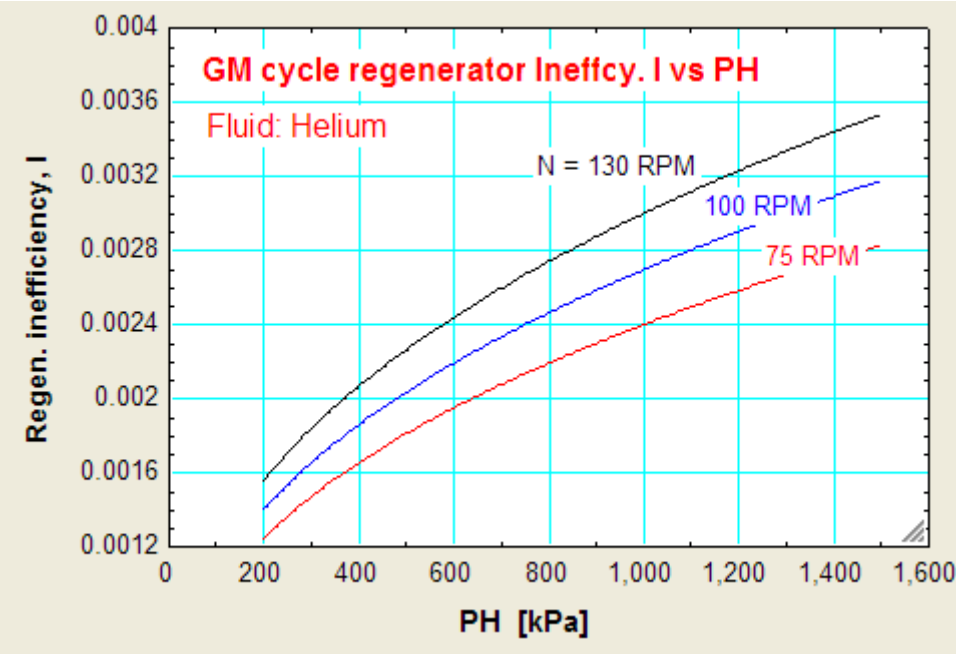
Plot:



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Prob. 4.3.23: Write a EES Function to find out the effectiveness of a regenerator by Λ-π method.

We shall use the built-in 2D Interpolation Function INTERPOLATE2DM in EES.

First, copy the Table of Effcy values for the regenerator for different values of Λ and ∏, given in Barron, in to a Lookout Table in EES, and name that Table as: 'Regen-Lambda_PI'. See below:

Regen-Lambda_PI

	Λ	Effcy(PI = 0)	Effcy(PI = 5)	Effcy(PI = 10)	Effcy(PI = 15)	Effcy(PI = 20)	Effcy(PI = 25)	Effcy(PI = 30)	Effcy(PI = 35)	Effcy(PI = 40)	Effcy(PI = 45)	Effcy(PI = 50)
Row 1		0	5	10	15	20	25	30	35	40	45	50
Row 2	0	0	0	0	0	0	0	0	0	0	0	0
Row 3	5	0.7143	0.639	0.469	0.326	0.25	0.202	0.167	0.143	0.125	0.112	0.1
Row 4	10	0.8333	0.809	0.738	0.61	0.494	0.402	0.333	0.284	0.25	0.222	0.2
Row 5	15	0.8824	0.866	0.84	0.784	0.693	0.585	0.498	0.43	0.375	0.332	0.3
Row 6	20	0.9091	0.9	0.886	0.856	0.811	0.756	0.651	0.578	0.5	0.443	0.4
Row 7	25	0.9259	0.92	0.911	0.895	0.871	0.827	0.77	0.698	0.62	0.555	0.5
Row 8	30	0.9375	0.933	0.927	0.918	0.903	0.881	0.845	0.797	0.727	0.654	0.598
Row 9	35	0.9459	0.943	0.939	0.932	0.922	0.907	0.888	0.856	0.81	0.754	0.692
Row 10	40	0.9524	0.95	0.947	0.942	0.935	0.925	0.912	0.891	0.865	0.82	0.773
Row 11	45	0.9574	0.955	0.953	0.949	0.944	0.938	0.928	0.914	0.898	0.871	0.835
Row 12	50	0.9615	0.961	0.958	0.955	0.951	0.946	0.939	0.929	0.915	0.897	0.875
Row 13	100	0.9804	0.98	0.979	0.979	0.978	0.977	0.976	0.975	0.973	0.972	0.97
Row 14	200	0.9901	0.99	0.989	0.989	0.989	0.989	0.989	0.988	0.988	0.988	0.988

Now, write the Function to get Effcy of regenerator when PI and LAMBDA are given, using the built-in INTERPOLATE2DM function in EES:

```
FUNCTION RegenEffcyLambdaPAI(PAI, LAMBDA)
    IF ((PAI < 0) OR (PAI > 50)) THEN
        CALL ERROR ('PAI should be between 0 and 50!')
    ENDIF
    IF ((LAMBDA < 0) OR (LAMBDA> 200)) THEN
        CALL ERROR ('LAMBDA should be between 0 and 200!')
    ENDIF
RegenEffcyLambdaPAI = INTERPOLATE2DM('Regen-Lambda_PI', PAI, LAMBDA)
END
```

"==========="

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Prob. 4.3.24: A regenerator is constructed of a matrix material with sp. heat = 1 kJ/kg.K, and a mass of 5.5 kg. The fluid flowing through the regenerator is a gas with sp. heat of 1.005 kJ/kg.K and a mass flow rate of 32 g/s for both heating and cooling periods. The heat transfer coeff for both the cooling and heating periods is 402 W/m^2.K and the surface area is 2.00 m^2. The heating and cooling periods are 2.5 minutes, each. Find the effectiveness of regenerator using the Lambda-PI method. [1]

EES Solution:

"Data:"

ms = 5.5 [kg] "…mass of solid"

cs = 1 [kJ/kg-K] "…. sp. heat of solid"

cpgas = 1.005 [kJ/kg-K] "… sp. heat of gas"

mdot = 0.032 [kg/s] "…mass flow rate of helium gas"

P = 2.5 * 60 "s…heating and cooling periods"

hc = 0.402[kW/m^2-K] "…heat transfer coeff."

As = 2.00 [m^2] "..surface area"

"Calculations:"

LAMBDA = hc * As / (mdot * cpgas) "…dimensionless length"

PAI = hc * As * P / (ms * cs) "…dimensionless period"

"Now, calculate the effcy by calling the Function:"

epsilon = RegenEffcyLambdaPAI(PAI, LAMBDA)

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Results:

Unit Settings: SI K kPa kJ mass deg

As = 2 [m^2]	cpgas = 1.005 [kJ/kg-K]	cs = 1 [kJ/kg-K]
ε = 0.854	hc = 0.402 [kW/m^2-K]	Λ = 25.0000
mdot = 0.032 [kg/s]	ms = 5.5 [kg]	P = 150 [s]
PAI = 21.93		

Thus:

PAI = 21.93

LAMBDA = 25.0

Effcy = 0.854 = 85.4% … Ans.

Prob.4.3.25 Write a EES Function to calculate the effectiveness of a regenerator by NTU-ε method, when CR = (Cmin/Cmax) = 1 (i.e. balanced regenerator).

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We have:

$$NTU_0 := \frac{1}{C_{min}} \cdot \left(\frac{1}{hh \cdot Ah} + \frac{1}{hc \cdot Ac} \right)^{-1}$$

$$C_R := \frac{C_{min}}{C_{max}}$$

$$C_m := \frac{ms \cdot cs}{P0 \cdot C_{min}}$$

$P_0 = P_h + P_c$

$f = 1/ P_0$

ε = Q_dot /[C_{min}. ($T_{h1} - T_{c1}$)]

When CR = 1:

Effcy values are given in Table 5.2 of Ref.[1] for a balanced regenerator (i.e. CR = 1), as a function of Cm and NTU_0.

When CR is not equal to 1:

First, find the 'effective values' of NTU and Cm:

$$NTU_e := \frac{2 \cdot NTU_0 \cdot C_R}{(1 + C_R)}$$

$$C_{me} := \frac{2 \cdot C_m \cdot C_R}{(1 + C_R)}$$

Using these effective values, find the effectiveness (ε1) for a 'balanced' regenerator from Table.

Then, determine following parameter 'X':

$$X := \frac{1 + C_R}{2 \cdot C_R} \cdot \frac{\varepsilon_1}{1 - \varepsilon_1} \cdot (1 - C_R)$$

Finally, regenerator effectiveness is calculated as:

$$\varepsilon := \frac{1 - \exp(-X)}{1 - C_R \cdot \exp(-X)}$$

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Now, copy the Table 5.2 in Ref.[1], in to a EES Lookout Table, with the Title: 'BalancedRegen_Effcy_NTU' as shown below:

NTU_0	EFFCY-Cm = 0.8	EFFCY-Cm = 1	EFFCY-Cm = 1.25	EFFCY-Cm = 1.5	EFFCY-Cm = 2	EFFCY-Cm = 3	EFFCY-Cm = 5	EFFCY-Cm = 1000000
	0.8	1	1.25	1.5	2	3	5	1,000,000
0	0	0	0	0	0	0	0	0
0.5	0.315	0.322	0.326	0.328	0.33	0.332	0.333	0.3333
1	0.449	0.467	0.478	0.485	0.491	0.496	0.499	0.5
1.5	0.521	0.548	0.566	0.576	0.586	0.594	0.598	0.6
2	0.566	0.601	0.623	0.636	0.649	0.659	0.664	0.6667
2.5	0.599	0.639	0.664	0.679	0.694	0.705	0.711	0.7143
3	0.622	0.667	0.696	0.712	0.728	0.74	0.746	0.75
3.5	0.642	0.69	0.721	0.738	0.755	0.767	0.774	0.7778
4	0.659	0.709	0.741	0.759	0.776	0.789	0.796	0.8
4.5	0.673	0.724	0.758	0.776	0.794	0.807	0.814	0.8182
5	0.685	0.738	0.772	0.791	0.809	0.822	0.829	0.8333
5.5	0.696	0.749	0.785	0.803	0.821	0.834	0.842	0.8462
6	0.705	0.759	0.796	0.814	0.832	0.845	0.853	0.8571
6.5	0.713	0.768	0.805	0.824	0.842	0.855	0.862	0.8667
7	0.721	0.776	0.814	0.833	0.85	0.863	0.87	0.875
7.5	0.728	0.784	0.822	0.84	0.858	0.871	0.878	0.8824
8	0.734	0.79	0.829	0.847	0.865	0.877	0.884	0.8889
8.5	0.74	0.796	0.835	0.854	0.871	0.883	0.89	0.8947
9	0.746	0.802	0.841	0.859	0.876	0.888	0.895	0.9
9.5	0.751	0.807	0.846	0.864	0.881	0.893	0.9	0.9048
10	0.756	0.811	0.851	0.869	0.886	0.898	0.904	0.9091
20	0.796	0.865	0.906	0.922	0.935	0.943	0.948	0.9524
30	0.816	0.889	0.928	0.943	0.947	0.961	0.964	0.9677
40	0.826	0.903	0.942	0.955	0.963	0.971	0.974	0.9756
50	0.834	0.914	0.951	0.962	0.97	0.975	0.978	0.9804
60	0.844	0.92	0.957	0.968	0.974	0.98	0.982	0.9836
90	0.862	0.935	0.969	0.977	0.982	0.986	0.987	0.989
100	0.867	0.939	0.971	0.979	0.984	0.987	0.989	0.9901
500	0.891	0.974	0.993	0.995	0.996	0.997	0.998	0.998

Note: The last column gives Effcy values for Cm = Infinity (taken as 10^6 here).

Now, write the desired Function to find effectiveness for any given NTU_0 and Cm, by 2D-linear interpolation, using the EES built-in function: INTERPLOATE2DM:

```
FUNCTION EffcyBalancedRegan_NTUmethod(Cm, NTU_0)

    IF ((Cm < 0.8) OR (Cm > 1000000)) THEN

        CALL ERROR ('Cm should be between 0.8 and 10^6!')

    ENDIF
```

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```
    IF ((NTU_0 < 0) OR (NTU_0> 500)) THEN

       CALL ERROR ('NTU_0 should be between 0 and 500!')

    ENDIF

EffcyBalancedRegan_NTUmethod = INTERPOLATE2DM('BalancedRegen_Effcy_NTU',
Cm, NTU_0)

END
```

"=="

Prob.4.3.26 Using the NTU-effectiveness method, determine the effectiveness for a valved type regenerator having a matrix material with a sp. heat of 0.48 kJ/kg.K and a total mass of 2688 kg. The mass flow rate of gas during the heating period is 2 kg/s and the mass flow rate during the cooling period is 1.8 kg/s. The sp. heat of gas for both the periods is 1.006 kJ/kg.K. The total period for the regenerator is 9 min. The convective heat transfer coeff for the heating period is 416 W/m^2.K and that for the cooling period is 388 W/m^2.K. The surface area for the heating and cooling periods is equal to 108 m^2 for each period. [1].

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EES Solution:

"Data:"

ms = 2688[kg]

cs = 0.48 [kJ/kg-K]

mdot_h = 2 [kg/s]

mdot_c = 1.8 [kg/s]

cph = 1.006 [kJ/kg-K]

cpc = 1.006 [kJ/kg-K]

P0 = 540 [s]

hh = 0.416 [kW/m^2-K]

hc = 0.388 [kW/m^2-K]

Ah = 108 [m^2]

Ac = 108 [m^2]

"Calculations:"

"Capacity rates:"

C_c = mdot_c * cpc

C_h = mdot_h * cph

"Since C_c < C_h, we have:"

C_min = C_c

C_max = C_h

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"Therefore: Capacity rate ratio"

C_R = C_min / C_max

"Since C_R = 0.9, i.e. not equal to 1, it is an 'Unbalanced Regenerator."

"Then:"

NTU_0 = (1 / C_min) * (1/(hh * Ah) + 1 / (hc * Ac))^(-1)

Cm = (ms * cs) / (P0 * C_min) ".. matrix capacity ratio"

"Calculate 'effective NTU' and 'effective Cm':"

NTU_e = (2 * NTU_0 * C_R) / (1 + C_R) "….effective NTU"

Cm_e = (2 * Cm * C_R) / (1 + C_R) "… effective Cm"

"For these effective values, find regen. effectiveness from the EES Function written above:"

epsilon_1 = EffcyBalancedRegan_NTUmethod(Cm_e, NTU_e)

"Now, find parameter X:"

X = ((1 + C_R) / (2 * C_R)) * (epsilon_1 / (1 – epsilon_1)) * (1 – C_R)

"Therefore: Regen. effectiveness:"

epsilon = (1 – exp(-X)) / (1 – C_R * exp(-X))

"=========="

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Results:

Unit Settings: SI K kPa kJ mass deg

A_c = 108 [m^2]	A_h = 108 [m^2]	C_m = 1.319
Cm_e = 1.25	c_{pc} = 1.006 [kJ/kg-K]	c_{ph} = 1.006 [kJ/kg-K]
cs = 0.48 [kJ/kg-K]	C_c = 1.811 [kW/K]	C_h = 2.012 [kW/K]
C_{max} = 2.012 [kW/K]	C_{min} = 1.811 [kW/K]	C_R = 0.9
ε = 0.8996	ε_1 = 0.8584	hc = 0.388 [kW/m^2-K]
hh = 0.416 [kW/m^2-K]	$mdot_c$ = 1.8 [kg/s]	$mdot_h$ = 2 [kg/s]
ms = 2.688 [kg]	NTU_0 = 11.97	NTU_e = 11.34
P0 = 540 [s]	X = 0.6398	

Thus:

Regen. effectiveness = epsilon = 0.8996 … Ans.

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Prob.4.3.27 A regenerator matrix is made of stacked wire screens having an equivalent dia of 0.4 mm. The free flow area through the screens is 0.003 m^2. Porosity of matrix is 0.675. The mean temp of air flowing through the regenerator is 200 K, and the gas properties are: μ = 13.3 μ Pa.s, cp = 1.006 kJ/kg.K and Pr = 0.739. The mass flow rate of air through the regenerator = 50 g/s. Determine the convective heat transfer coeff between the air and matrix material. [1].

Also, plot the convective heat transfer coeff as the mass flow rate varies from 30 g/s to 100 g/s

EES Solution:

For stacked wire screens, we have, for Colburn j-factor and friction factor [1]:

$$n = 0.37 + \frac{0.0136 \cdot e_v}{1 - e_v} \qquad jH = \frac{0.2 \cdot Re^{-n}}{1 - e_v}$$ ...Colburn j-factor

$$f = \frac{860 \cdot (1 - e_v)}{Re} + \frac{2.2 \cdot e_v}{Re^{0.1}}$$ ...friction factor

"Data:"

d_e = 0.0004 [m] "..equiv. dia"

A_ff = 0.003 [m^2] "… free flow area"

e_v = 0.675 "…porosity"

T_m = 200 [K]

{mdot = 0.05 [kg/s]}

"Gas props at T_m = 200 K:"

mu = 13.3E-06 [Pa-s]

cp = 1.006 [kJ/kg-K]

Pr = 0.739

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"Calculations:"

G = mdot / A_ff "…kg/m^2-s… mass velocity"

Re = G * d_e / mu "… Reynolds No."

"Colburn j factor:"

n = 0.37 + (0.0136 * e_v) / (1 – e_v)

jH = (0.2 * Re^(-n)) / (1 – e_v)

"But, jH = (hc / (cp * G)) / * Pr^(2/3) "

"Therefore: heat transfer coeff, hc:"

hc = (jH * cp * G) / Pr^(2/3)

Results:

Unit Settings: SI K kPa kJ mass deg

A_{ff} = 0.003 [m^2]	cp = 1.006 [kJ/kg-K]	d_e = 0.0004 [m]
e_v = 0.675	G = 16.67 [kg/m^2-s]	hc = 1.061 [kW/m^2-K]
jH = 0.05174	mdot = 0.05 [kg/s]	μ = 0.0000133 [Pa-s]
n = 0.3982	Pr = 0.739	Re = 501.3
T_m = 200 [K]		

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Thus:

Convective heat transfer coeff. = hc = 1.061 kW/m^2-K … Ans.

Also, plot the convective heat transfer coeff as the mass flow rate varies from 30 g/s to 100 g/s:

First, compute the Parametric Table:

1..8	1 mdot [kg/s]	2 jH	3 hc [kW/m2-K]
Run 1	0.03	0.06342	0.7805
Run 2	0.04	0.05655	0.928
Run 3	0.05	0.05174	1.061
Run 4	0.06	0.04812	1.184
Run 5	0.07	0.04525	1.3
Run 6	0.08	0.04291	1.408
Run 7	0.09	0.04094	1.512
Run 8	0.1	0.03926	1.611

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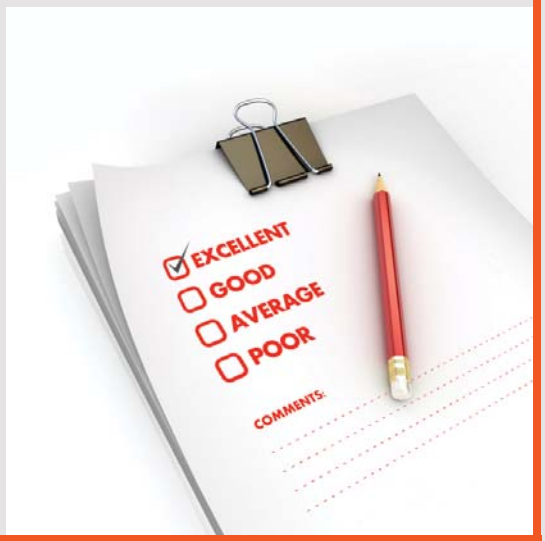

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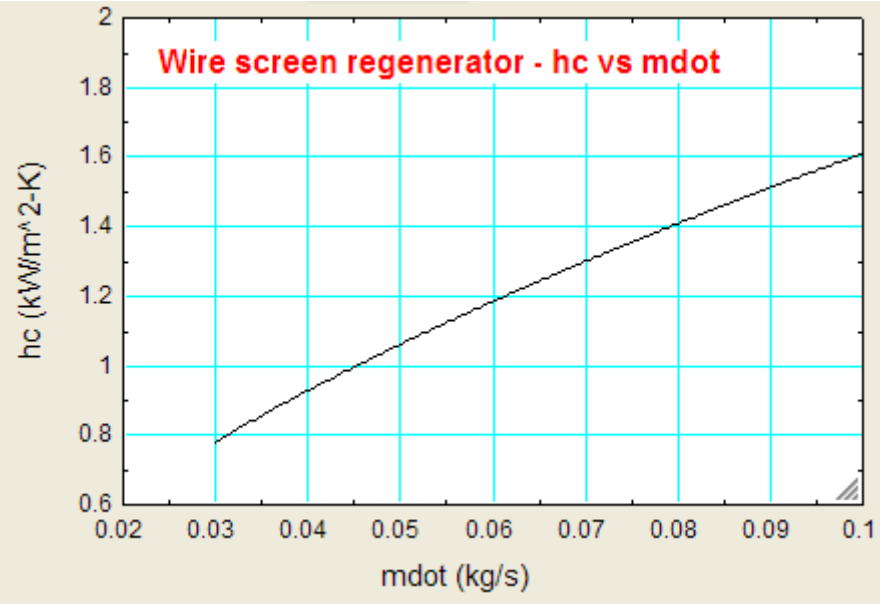
Now, plot:



Prob.4.3.28 Nitrogen gas at an average temp of 200 K and an average pressure of 506.6 kPa flows through a regenerator matrix made of 3 mm dia random stacked spheres at a mass flow rate of 20 g/s. Porosity of matrix is 0.4 and the matrix is contained in a tube having an inside dia of 80 mm and a length of 750 mm. The properties of nitrogen gas are: μ = 12.95 μ Pa.s, ρ = 8.56 kg/m^3. Determine the pressure drop of nitrogen flowing through the regenerator. [1].

Also, plot ΔP vs mdot as mdot varies from 20 g/s to 70 g/s.

For random stacked spheres, we have, for Colburn j-factor and friction factor [1]:

$$jH = \frac{h_c \cdot Pr^{\frac{2}{3}}}{G \cdot cp} = 0.255 \cdot (e_v \cdot Re)^{\frac{-1}{3}} \qquad G = \frac{mdot}{A_{ff}} \qquad A_{ff} = \frac{e_v \cdot V_0}{L}$$

$$f = \frac{1 - e_v}{e_v} \cdot \left[\frac{570 \cdot (1 - e_v)^2}{e_v \cdot Re} + 3.5 \right] \qquad A = \frac{6 \cdot (1 - e_v) \cdot V_0}{D_s}$$

$$\Delta P = \left(\frac{f \cdot L}{D_s} \right) \cdot \left(\frac{G^2}{2 \cdot \rho} \right)$$

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EES Solution:

"Data:"

D_s = 0.003 [m] "…dia of spheres"

mdot = 0.02 [kg/s] "…mass flow rate of N2 gas"

e_v = 0.4 " … porosity"

d_i = 0.08 [m] "…inside dia of tube"

L = 0.75 [m] "…length of tube"

"Gas properties:"

mu = 12.95E-06 [Pa-s] "…dyn. viscosity of gas"

rho = 8.56 [kg/m^3] "… density of gas"

"Calculations:"

V_0 = (pi * d_i^2/4) * L "m^3 …. tube volume"

A_ff = e_v * V_0 / L "m^2 .. frree flow area"

G = mdot / A_ff "…kg/m^2-s … mass velocity"

Re = G * D_s / mu " .. Reynolds No."

f = ((1 – e_v) / e_v) * (((570 * (1 – e_v)^2) / (e_v * Re)) + 3.5) "….friction factor"

"Pressure drop:"

DELTAP = (f * L / D_s) * (G^2 /(2 * rho)) "Pa"

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Results:

Unit Settings: SI K kPa kJ mass deg

A_{ff} = 0.002011 [m^2]	ΔP = 8,068 [Pa]	d_i = 0.08 [m]
D_s = 0.003 [m]	e_v = 0.4	f = 5.584
G = 9.947 [kg/m^2-s]	L = 0.75 [m]	mdot = 0.02 [kg/s]
μ = 0.00001295 [Pa-s]	Re = 2,304	ρ = 8.56 [kg/m^3]
V_0 = 0.00377 [m^3]		

Thus:

Reynolds No., Re = 2304 … Ans.

Friction factor, f = 5.584 … Ans.

Pressure drop, ΔP = 8068 Pa … Ans.

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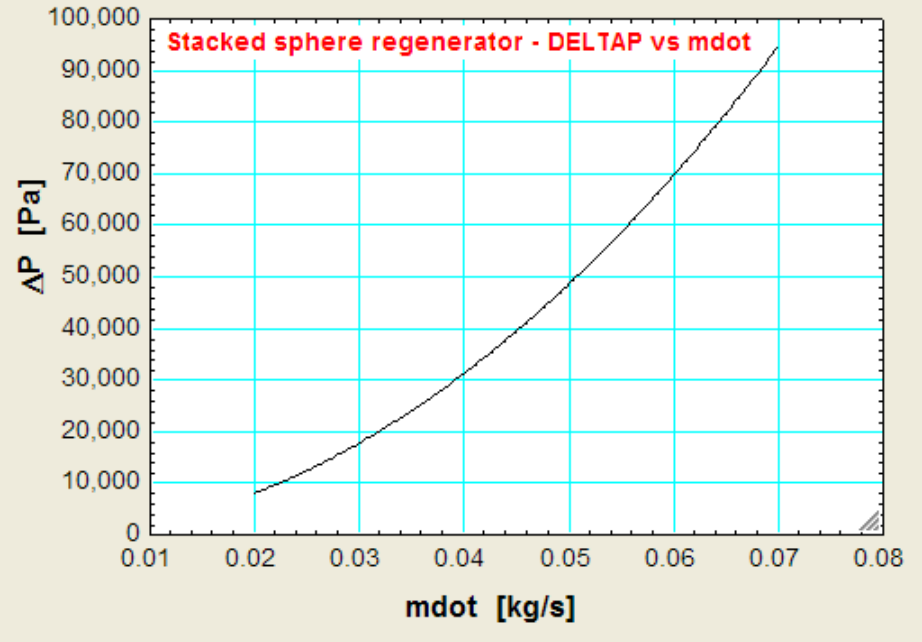
Also, plot ΔP vs mdot as mdot varies from 20 g/s to 70 g/s:

First, compute the Parametric Table:

1..6	1 mdot [kg/s]	2 Re	3 f	4 ΔP [Pa]
Run 1	*0.02*	2,304	5.584	8,068
Run 2	*0.03*	3,457	5.473	17,792
Run 3	*0.04*	4,609	5.417	31,308
Run 4	*0.05*	5,761	5.384	48,617
Run 5	*0.06*	6,913	5.361	69,719
Run 6	*0.07*	8,065	5.345	94,614

Now, plot:



Prob.4.3.29 Write a EES Procedure for Brillouin function and entropy as a function of Brillouin constant ξ and atomic constant J. Tabulate the results and draw the graphs.

Solution:

Brillouin function and entropy for paramagnetic materials:

Brillouin function:

$$B(\xi, J) := (2 \cdot J + 1) \cdot \coth((2 \cdot J + 1) \cdot \xi) - \coth(\xi)$$

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where

$$\xi = \frac{g \cdot \mu_B \cdot \mu_0 \cdot H}{2 \cdot k \cdot T}$$ ... Brillouin dimensionless parameter

Entropy:

$$\frac{s}{R} = \ln(2 \cdot J + 1)$$ ...for H = 0

$$sbyR(\xi, J) := \ln\left[\frac{\sinh((2 \cdot J + 1) \cdot \xi)}{\sinh(\xi)}\right] - \xi \cdot B(\xi, J)$$

EES Procedure:

PROCEDURE Brillouin_Function_entropy(Xi, J: B, sbyR)

"Gives Brillouin Function, B and s/R for a paramagnetic material"

"Inputs: Brillouin dimensionless parameter, Xi, Atomic constant, J"

"Outputs: Brillouin function, B, and sbyR where s = entropy, R = gas const."

B:= (2 * J + 1) * (1 / tanh((2*J + 1) * Xi)) – 1/ tanh(Xi)

sbyR = ln(Sinh((2*J + 1) * Xi) / Sinh(Xi)) – Xi * B

END

"=="

Program:

Xi = 0.3

J = 1/2

CALL Brillouin_Function_entropy(Xi, J: B, sbyR)

"=="

Results:

Unit Settings: SI K kPa kJ mass deg

B = 0.2913	J = 0.5	sbyR = 0.6501	ξ = 0.3

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To plot the graphs:

The Parametric Table:

	J = 1/2	J = 1/2	J = 3/2	J = 3/2	J = 5/2	J = 5/2	J = 7/2	J = 7/2
ξ	BrillouinFunction	sbyR	BrillouinFunction	sbyR	BrillouinFunctio	sbyR	BrillouinFunction	sbyR
1.000E-06	-0.00002626	0.6931	-0.000006378	1.386	-0.00001026	1.792	-0.00001013	2.079
0.1	0.09967	0.6882	0.4944	1.362	1.139	1.736	2.014	1.981
0.2	0.1974	0.6735	0.9573	1.293	2.131	1.588	3.613	1.745
0.3	0.2913	0.6501	1.365	1.191	2.904	1.397	4.7	1.478
0.4	0.3799	0.6191	1.708	1.072	3.468	1.201	5.395	1.237
0.5	0.4621	0.5822	1.985	0.9475	3.866	1.023	5.841	1.038
0.6	0.537	0.5411	2.204	0.8275	4.147	0.8695	6.139	0.8749
0.7	0.6044	0.4974	2.375	0.7169	4.348	0.7393	6.346	0.7412
0.8	0.664	0.4527	2.507	0.618	4.495	0.6296	6.494	0.6302
0.9	0.7163	0.4083	2.61	0.531	4.604	0.5369	6.604	0.5371
1	0.7616	0.3653	2.69	0.4554	4.687	0.4584	6.687	0.4584
1.1	0.8005	0.3245	2.752	0.3901	4.751	0.3916	6.751	0.3916
1.2	0.8337	0.2865	2.801	0.3338	4.8	0.3345	6.8	0.3345
1.3	0.8617	0.2514	2.84	0.2854	4.84	0.2858	6.84	0.2858
1.4	0.8854	0.2195	2.871	0.2439	4.871	0.244	6.871	0.244
1.5	0.9051	0.1909	2.895	0.2082	4.895	0.2083	6.895	0.2083
1.6	0.9217	0.1653	2.915	0.1776	4.915	0.1776	6.915	0.1776
1.7	0.9354	0.1426	2.931	0.1513	4.931	0.1513	6.931	0.1513
1.8	0.9468	0.1227	2.944	0.1288	4.944	0.1288	6.944	0.1288
1.9	0.9562	0.1053	2.954	0.1096	4.954	0.1096	6.954	0.1096
2	0.964	0.09009	2.963	0.09311	4.963	0.09311	6.963	0.09311
2.5	0.9866	0.04018	2.986	0.04068	4.986	0.04068	6.986	0.04068
3	0.9951	0.01731	2.995	0.01739	4.995	0.01739	6.995	0.01739
3.5	0.9982	0.007289	2.998	0.007301	4.998	0.007301	6.998	0.007301
4	0.9993	0.003018	2.999	0.00302	4.999	0.00302	6.999	0.00302

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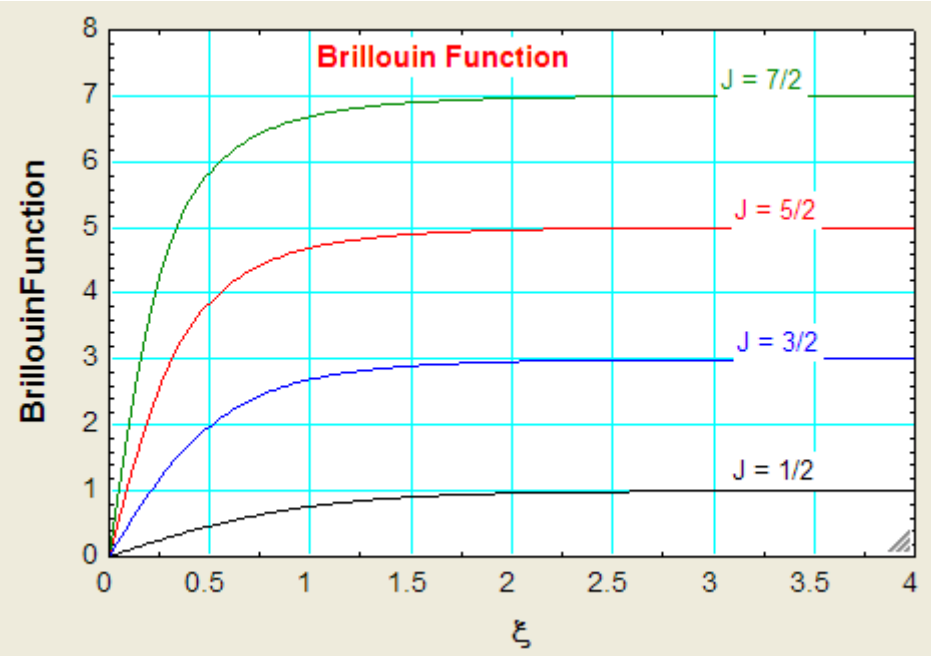
Now, plot the graphs:



Prob.4.3.30 Write a EES Procedure to get properties of given paramagnetic material:

PROCEDURE Props_Paramag(Material: MaterialName$, Lande_g, J, M, R, C)

"Gives properties of a paramagnetic material"

```
"Inputs: Material:
1 = Cerium ethyl sulfate
2 = Cerium magnesium nitrate
3 = Chromium methylammonium alum
4 = Chromium potassium alum
5 = Copper potassium sulfate
6 = Gadolinium sulfate
7 = Iron ammonium alum
8 = Manganese ammonium sulfate
9 = Titanium cesium alum  "
```

"Outputs:
Materal Name,
Lande splitting factor, g,
Ionic const. J,

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Ionic wt., M (kg/mol),
Gas const. R, (J/kg.K) and
Curie const., C (K-m3/kg)"

"Write the properties in a (9 × 6) Matrix: "

"Material No., g J M R C"

Props[1,1..6] = [1, 1.7,1.00, 0.678, 12.263, 2.51E-05]

Props[2,1..6] = [2, 1.84, 0.50, 0.765, 10.868, 5.22E-06]

Props[3,1..6] = [3, 2, 1.50, 0.492, 16.899, 3.05E-05]

Props[4,1..6] = [4, 1.97, 1.50, 0.499, 16.662, 4.58E-05]

Props[5,1..6] = [5, 2.14, 0.50, 0.442, 18.811, 1.221E-05]

Props[6,1..6] = [6, 1.992, 3.50, 0.373, 22.29, 2.633E-04]

Props[7,1..6] = [7, 2, 2.50, 0.482, 17.25, 1.141E-04]

Props[8,1..6] = [8, 2.06, 2.50, 0.391, 21.264, 1.492E-04]

Props[9,1..6] = [9, 1.89, 0.50, 0.589, 14.116, 4.21E-06]

IF (Material = 1) THEN MaterialName$ = 'Cerium_ethyl_sulfate'

IF (Material = 2) THEN MaterialName$ = 'Cerium magnesium nitrate'

IF (Material = 3) THEN MaterialName$ = 'Chromium methylammonium alum'

IF (Material = 4) THEN MaterialName$ = 'Chromium potassium alum'

IF (Material = 5) THEN MaterialName$ = 'Copper potassium sulfate'

IF (Material = 6) THEN MaterialName$ = 'Gadolinum sulfate'

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IF (Material = 7) THEN MaterialName$ = 'Iron ammonium alum'

IF (Material = 8) THEN MaterialName$ = 'Manganese ammonium sulfate'

IF (Material = 9) THEN MaterialName$ = 'Titanium cesium alum'

Lande_g := Props[Material,2]

J := Props[Material,3]

M := Props[Material,4]

R := Props[Material,5]

C := Props[Material,6]

END

"================================"

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"Example:"

Material = 3

CALL Props_Paramag(Material: MaterialName$, Lande_g, J, M, R, C)

Results:

Unit Settings: SI K kPa kJ mass deg

C = 3.050E-05 [K-m^3/kg]
Lande$_g$ = 2
Material = 3
R = 16.899 [J/kg-K]

J = 1.5
M = 0.492 [kg/mol]
MaterialName$ = 'Chromium methylammonium alum'

Prob.4.3.31 Determine the magnetic moment per unit mass and entropy for gadolinium sulfate at 0.1 K in a magnetic field of 60 kA/m (75.4 mT) assuming that Brillouin expression is valid at this condition.[1]

Solution:

We have, for Magnetic moment:

$I = (1/2).n.g.\ \mu_B.B(\xi)$

Props of Gadolinium sulfate:

Using the EES Procedure written above:

Material = 6 … for Gadolinium sulfate

We have:

Material = 6

CALL Props_Paramag(Material: MaterialName$, Lande_g, J, M, R, C)

We get:

Unit Settings: SI K kPa kJ mass deg

C = 2.6330E-04 [K-m^3/kg]
Lande$_g$ = 1.992
Material = 6
R = 22.290 [J/kg-K]

J = 3.5
M = 0.373 [kg/mol]
MaterialName$ = 'Gadolinum sulfate'

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"Therefore, we have:"

M = 0.373 [kg/mol] "…Ionic weight,"

Lande_g = 1.992 "….Lande splitting factor"

J = 7/2

"Also:"

H = 60 * 10^3 [A/m]

N_0 = 6.023 * 10^23 "per mol … Avogadro's No."

mu_B = 0.9273 * 10^(-23) "[A-m^2] … Bohr magneton"

mu_0 = 4 * pi * 10^(-7) "[J/A-m^2] …permeability of free space"

k = 1.3805 * 10^(-23) [J/K] "…Boltzmann constant"

n = N_0 / M "…no. of ions per unit mass"

T = 0.1 [K] "Temp (K)"

"Now, we have, Brillouin parameter:"

Xi = Lande_g * mu_B * mu_0 * H / (2 * k * T)

"Therefore: Brillouin function:"

CALL Brillouin_Function_entropy(Xi, J: B, sbyR)

We get:

Unit Settings: SI K kPa kJ mass deg

B = 5.857	H = 60,000 [A/m]	J = 3.5
k = 1.380E-23 [J/K]	$Lande_g$ = 1.992	M = 0.373 [kg/mol]
μ_0 = 0.000001257 [J/A-m^2]	μ_B = 9.273E-24 [A-m^2]	n = 1.615E+24 [per·kg]
N_0 = 6.023E+23	sbyR = 1.03	T = 0.1 [K]
ξ = 0.5044		

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"i.e. We get:

Brillouin_Function, B = 5.8572"

"And, Magnetic moment, I:"

B = 5.8572

I = (1/2) * n * Lande_g * mu_B * B

We get:

Unit Settings: SI K kPa kJ mass deg

B = 5.857	H = 60,000 [A/m]
I = 87.3522 [A-m^2/kg]	J = 3.5
k = 1.380E-23 [J/K]	Lande$_g$ = 1.992
M = 0.373 [kg/mol]	μ_0 = 0.000001257 [J/A-m^2]
μ_B = 9.273E-24 [A-m^2]	n = 1.615E+24 [per·kg]
N_0 = 6.023E+23	T = 0.1 [K]
ξ = 0.5044	

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i.e.

Magnetic moment, I = 87.3522 A-m^2/kg … Ans.

"To find entropy:"

"We have:"

R = 22.29 [J/kg-K]

sbyR = 1.03

"Therefore, entropy:"

s = R * sbyR

We get:

Unit Settings: SI K kPa kJ mass deg

B = 5.857	H = 60.000 [A/m]	I = 87.3522 [A-m^2/kg]
J = 3.5	k = 1.380E-23 [J/K]	Lande$_g$ = 1.992
M = 0.373 [kg/mol]	μ_0 = 0.000001257 [J/A-m^2]	μ_B = 9.273E-24 [A-m^2]
n = 1.615E+24 [per·kg]	N_0 = 6.023E+23	R = 22.290 [J/kg-K]
s = 22.96 [J/kg-K]	sbyR = 1.03	T = 0.1 [K]
ξ = 0.5044		

i.e. Entropy = s = 22.96 J/kg-K … Ans.

Prob.4.3.32 Determine the magnetic moment per unit mass and entropy for cerium magnesium nitrate at 0.1 K in a magnetic field of 189 kA/m (0.2375 T) assuming that Brillouin expression is valid at this condition. What would be the value of magnetic moment per unit mass according to the Curie law?[1]

Solution:

We have:

$$\xi = \frac{g \cdot \mu_B \cdot \mu_0 \cdot H}{2 \cdot k \cdot T}$$ … Brillouin dimensionless parameter

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And for CMN, we have:

Using the EES Procedure written above:

Material = 2 … for Cerium magnesium nitrate

We get:

Material = 2

CALL Props_Paramag(Material: MaterialName$, Lande_g, J, M, R, C)

Unit Settings: SI K kPa kJ mass deg

C = 5.2200E-06 [K-m^3/kg]

Lande$_g$ = 1.84

Material = 2

R = 10.868 [J/kg-K]

J = 0.5

M = 0.765 [kg/mol]

MaterialName$ = 'Cerium magnesium nitrate'

"Therefore, we have:"

M = 0.765 [kg/mol] "…Ionic weight,"

Lande_g = 1.84 "….Lande splitting factor"

J = 1/2

"Also:"

H = 189 * 10^3 [A/m]

N_0 = 6.023 * 10^23 "per mol …. Avogadro's No."

mu_B = 0.9273 * 10^(-23) "[A-m^2] .. Bohr magneton"

mu_0 = 4 * pi * 10^(-7) "[J/A-m^2] …permeability of free space"

k = 1.3805 * 10^(-23) [J/K] "…Boltzmann constant"

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n = N_0 / M "…no. of ions per unit mass"

T = 0.1 [K] "Temp (K)"

"Now, we have, Brillouin parameter:"

Xi = Lande_g * mu_B * mu_0 * H / (2 * k * T)

"Therefore: Brillouin function:"

CALL Brillouin_Function_entropy(Xi, J: B, sbyR)

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We get:

Unit Settings: SI K kPa kJ mass deg

B = 0.8991	H = 189,000 [A/m]	J = 0.5
k = 1.380E-23 [J/K]	$Lande_g$ = 1.84	M = 0.765 [kg/mol]
μ_0 = 0.000001257 [J/A-m^2]	μ_B = 9.273E-24 [A-m^2]	n = 7.873E+23 [per·kg]
N_0 = 6.023E+23	sbyR = 0.1998	T = 0.1 [K]
ξ = 1.468		

"i.e. We get:

Brillouin_Function, B = 0.8991"

"And, Magnetic moment, I:"

B = 0.8991

I = (1/2) * n * Lande_g * mu_B * B

"To find entropy:"

"We have:"

R = 10.868 [J/kg-K]

sbyR = 0.1998

"Therefore, entropy:"

s = R * sbyR

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Results:

Unit Settings: SI K kPa kJ mass deg

B = 0.8991
I = 6.0390 [A-m^2/kg]
k = 1.380E-23 [J/K]
M = 0.765 [kg/mol]
μ_B = 9.273E-24 [A-m^2]
N_0 = 6.023E+23
s = 2.171 [J/kg-K]
T = 0.1 [K]

H = 189.000 [A/m]
J = 0.5
Lande$_g$ = 1.84
μ_0 = 0.000001257 [J/A-m^2]
n = 7.873E+23 [per·kg]
R = 10.868 [J/kg-K]
sbyR = 0.1998
ξ = 1.468

Thus:

Magnetic moment per unit mass = I = 6.039 A-m^2/kg … Ans.

Entropy = s = 2.171 J/kg-K … Ans.

"If the Curie Law is valid:"

"We have, Curie const. for CMN:"

C = 5.22 * 10^(-6) [k-m^3/kg]

"Then, Magnetic momet, I:"

I_curie = C * H / T

We get:

Unit Settings: SI K kPa kJ mass deg

B = 0.8991
I = 6.0390 [A-m^2/kg]
k = 1.380E-23 [J/K]
μ_0 = 0.000001257 [J/A-m^2]
N_0 = 6.023E+23
sbyR = 0.1998

C = 5.2200E-06 [K-m^3/kg]
I$_{curie}$ = 9.866 [A-m^2/kg]
Lande$_g$ = 1.84
μ_B = 9.273E-24 [A-m^2]
R = 10.868 [J/kg-K]
T = 0.1 [K]

H = 189.000 [A/m]
J = 0.5
M = 0.765 [kg/mol]
n = 7.873E+23 [per·kg]
s = 2.171 [J/kg-K]
ξ = 1.468

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i.e. Magnetic moment, when Curie Law is valid:

I_curie = 9.866 A-m^2/kg … Ans.

Prob.4.3.33 Magnetic field intensity around a cerium magnesium nitrate (CMN) pellet is decreased reversibly and adiabatically from 320 kA/m (0.402 T) to 32 kA/m (40.2 mT). If the initial temp is 2 K, determine the final temp. [1]

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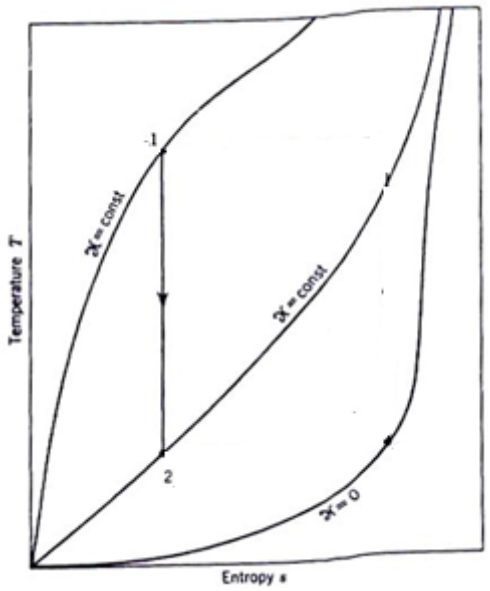

EES Solution:

"We have, for CMN:"

M = 0.765 [kg/mol] "…Ionic weight,"

Lande_g = 1.84 "….Lande splitting factor"

J = 1/2

"Also:"

H1 = 320 * 10^3 [A/m]

H2 = 32 * 10^3[A/m]

N_0 = 6.023 * 10^23 "per mol … Avogadro's No."

mu_B = 0.9273 * 10^(-23) "[A-m^2] … Bohr magneton"

mu_0 = 4 * pi * 10^(-7) "[J/A-m^2] … permeability of free space"

k = 1.3805 * 10^(-23) [J/K] "…Boltzmann constant"

n = N_0 / M "…no. of ions per unit mass"

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T1 = 2 [K] "Temp (K)"

"Now, we have, Brillouin parameter:"

Xi = Lande_g * mu_B * mu_0 * H1 / (2 * k * T1)

"Now, we have, Brillouin parameter, and entropy:"

Xi = Lande_g * mu_B * mu_0 * H1 / (2 * k * T1)

"Therefore: Brillouin function:"

CALL Brillouin_Function_entropy(Xi, J: B, sbyR)

We get:

Unit Settings: SI K kPa kJ mass deg

B = 0.1236	H1 = 320.000 [kJ/kg]	H2 = 32.000 [kJ/kg]
J = 0.5	k = 1.380E-23 [J/K]	$Lande_g$ = 1.84
M = 0.765 [kg/mol]	μ_0 = 0.000001257 [J/A-m^2]	μ_B = 9.273E-24 [A-m^2]
n = 7.873E+23 [per·kg]	N_0 = 6.023E+23	sbyR = 0.6855
T1 = 2 [K]	ξ = 0.1243	

"i.e. We have:

Brillouin_Function, B = 0.1236"

"And, Entropy:"

"We have:"

R = 10.868 [J/kg-K]

sbyR = 0.6855

"Therefore, entropy before demagnetization:"

s1 = R * sbyR

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"Let T2 be the temp at the end of adiabatic demagnetization. And, s2 = s1."

Xi_2 = Lande_g * mu_B * mu_0 * H2 / (2 * k * T2) "..Brillouin dimensionless parameter for the case after demagnetization:"

"Then, we get, using the EES Procedure for Brillouin Function and Entropy:"

CALL Brillouin_Function_entropy(Xi_2, J: B, sbyR)

We get:

Unit Settings: SI K kPa kJ mass deg

B = 0.1235	H1 = 320.000 [kJ/kg]	H2 = 32.000 [A/m]
J = 0.5	k = 1.380E-23 [J/K]	$Lande_g$ = 1.84
M = 0.765 [kg/mol]	μ_0 = 0.000001257 [J/A-m^2]	μ_B = 9.273E-24 [A-m^2]
n = 7.873E+23 [per·kg]	N_0 = 6.023E+23	R = 10.868 [J/kg-K]
s1 = 7.45 [J/kg-K]	sbyR = 0.6855	T1 = 2 [K]
T2 = 0.2002 [K]	ξ = 0.1243	ξ_2 = 0.1241

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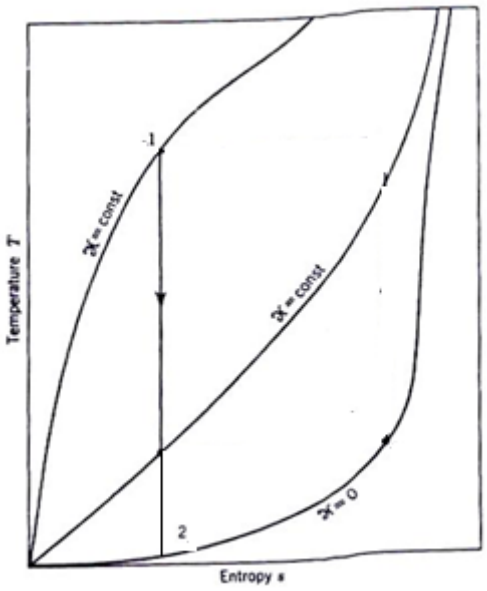
Thus:

Temp. before demagnetization, T1 = 2 K

Temp. after demagnetization, T2 = 0.02002 K … Ans.

Entropy = s1 = s2 = 7.45 J/kg.K … Ans.

Prob.4.3.34 Magnetic field intensity around an iron ammonium alum pellet is decreased reversibly and adiabatically from 500 kA/m (0.628 T) to zero (external field). If the "internal field" for iron ammonium alum is 35 kA/m (44 mT), and the initial temp of the pellet is 1.5 K, determine the final temp. of the pellet. [1]



EES Solution:

"Props of Iron ammonium alum:

Material = 7 … for Iron ammonium alum

Using the EES Procedure written above, we have:"

Material = 7

CALL Props_Paramag(Material: MaterialName$, Lande_g, J, M, R, C)

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We get:

Unit Settings: SI K kPa kJ mass deg

C = 1.1410E-04 [K-m^3/kg]

Lande$_g$ = 2

Material = 7

R = 17.250 [J/kg-K]

J = 2.5

M = 0.482 [kg/mol]

MaterialName$ = 'Iron ammonium alum'

"i.e. we get:"

J = 5/2

Lande_g = 2

R = 17.25 [J/kg-K]

M = 0.482 [kg/mol]

T1 = 1.5 [K]

H1 = 500 * 10^3 [A/m]

H2 = 0 [A/m]

H_int = 35 * 10^3 [A/m] "…Internal magnetic field"

"Also:"

N_0 = 6.023 * 10^23 " per mol … Avogadro's No."

mu_B = 0.9273 * 10^(-23) "[A-m^2] … Bohr magneton"

mu_0 = 4 * pi * 10^(-7) "[J/A-m^2] …permeability of free space "

k = 1.3805 * 10^(-23) [J/K] "…Boltzmann constant"

n = N_0 / M "…no. of ions per unit mass"

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"Clculations:"

"Effective magn. fields:"

H1_eff = (H1^2 + H_int^2)^(1/2) "A/m"

H2_eff = (H2^2 + H_int^2)^(1/2) "A/m"

"Then:"

Xi_1 = Lande_g * mu_B * mu_0 * H1_eff / (2 * k * T1)

"Then, find sbyR:"

CALL Brillouin_Function_entropy(Xi_1, J: B, sbyR)

"Then, Entropy:"

s1 = R * sbyR

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We get:

Unit Settings: SI K kPa kJ mass deg

B = 2.782	H1 = 500.000 [kJ/kg]	$H1_{eff}$ = 501.224
H2 = 0 [A/m]	$H2_{eff}$ = 35.000	H_{int} = 35.000
J = 2.5	k = 1.380E-23 [J/K]	$Lande_g$ = 2
M = 0.482 [kg/mol]	μ_0 = 0.000001257 [J/A-m^2]	μ_B = 9.273E-24 [A-m^2]
n = 1.250E+24 [per·kg]	N_0 = 6.023E+23	R = 17.250 [J/kg-K]
s1 = 24.71 [J/kg-K]	sbyR = 1.432	T1 = 1.5 [K]
ξ_1 = 0.2821		

Note that initial entropy, before demagnetization, s1 = 24.71 J/kg-K.

After demagentizaton:

"Let T2 be the temp at the end of adiabatic demagnetization. And, s2 = s1. i.e. sbyR remains the same."

"We get:"

sbyR = 1.432

CALL Brillouin_Function_entropy(Xi_2, J: B, sbyR) "… finds Xi_2"

Xi_2 = Lande_g * mu_B * mu_0 * H2_eff / (2 * k * T2) "… finds T2"

Results:

Unit Settings: SI K kPa kJ mass deg

B = 2.784	H1 = 500.000 [kJ/kg]	$H1_{eff}$ = 501.224
$H2_{eff}$ = 35.000	H2 = 0 [A/m]	H_{int} = 35.000
J = 2.5	k = 1.380E-23 [J/K]	$Lande_g$ = 2
M = 0.482 [kg/mol]	μ_0 = 0.000001257 [J/A-m^2]	μ_B = 9.273E-24 [A-m^2]
n = 1.250E+24 [per·kg]	N_0 = 6.023E+23	R = 17.250 [J/kg-K]
sbyR = 1.432	T1 = 1.5 [K]	T2 = 0.1047 [K]
ξ_2 = 0.2823		

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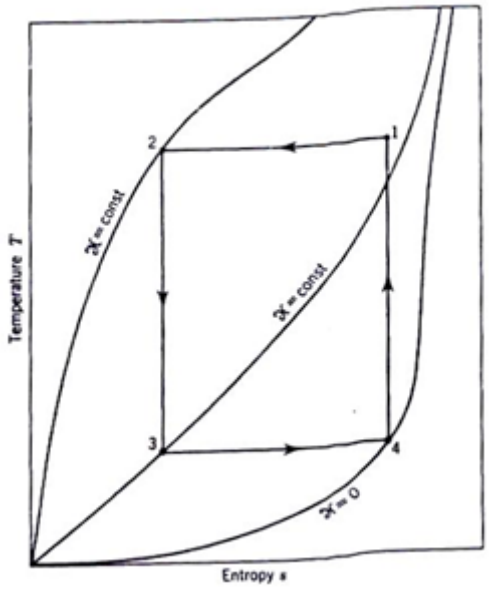
Thus:

Final temp after demagnetization = T2 = 0.1047 K … Ans.

Prob.4.3.35 A magnetic refrigerator operates between 0 kA/m and 231.3 kA/m (0.291 T) during the reversible isothermal heat addition process. Heat is added to the salt from the low temp region at 0.22 K and heat is rejected to a helium bath at 2.5 K. The mass of the working salt is 25 g. and the refrigerator operates at 30 cycles per hour. Determine the heat transfer rate from the low temp source to the refrigerator, assuming the Brillouin expression is valid. The working salt is Chromium potassium alum. [1]



EES Solution:

"Props of Chromium potassium alum:"

"Use the EES Procedure written earlier:"

Material = 4

CALL Props_Paramag(Material: MaterialName$, Lande_g, J, M, R, C)

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We get:

Unit Settings: SI K kPa kJ mass deg

C = 4.5800E-05 [K-m^3/kg]

Lande$_g$ = 1.97

Material = 4

R = 16.662 [J/kg-K]

J = 1.5

M = 0.499 [kg/mol]

MaterialName$ = 'Chromium potassium alum'

"Further:"

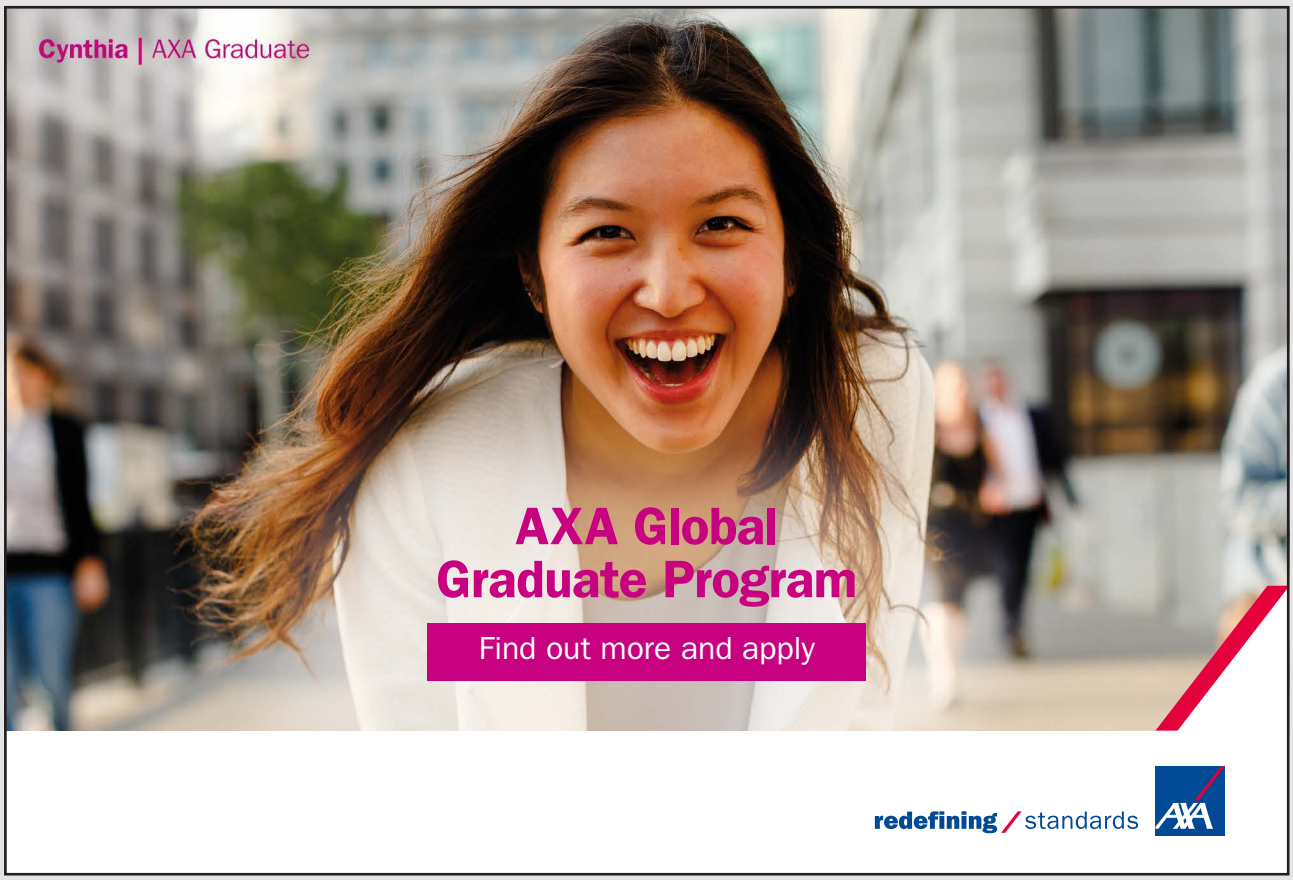
m = 0.025 [kg] ".. mass of pellet"

N_0 = 6.023 * 10^23 "per mol …. Avogadro's No."

mu_B = 0.9273 * 10^(-23) "[A-m^2] … Bohr magneton"

mu_0 = 4 * pi * 10^(-7) "[J/A-m^2] …permeability of free space"

k = 1.3805 * 10^(-23) [J/K] "…Boltzmann constant"



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n = N_0 / M "…no. of ions per unit mass"

T4 = 0.22[K]

H2 = 231.3 * 10^3 [A/m]

H4 = 0 [A/m]

T2 = 2.5 [K]

Lande_g = 1.97

J = 3/2

R = 16.662 [J/kg-K]

"Therefore:"

Xi_2 = Lande_g * mu_B * mu_0 * H2 / (2 * k * T2)

"And, get s2byR using the EES Procedure for Brillouin Function:"

CALL Brillouin_Function_entropy(Xi_2, J: B, s2byR)

"Therefore:"

s2 = R * s2byR "J/kg-K"

"Now, s3 = s2 for isentropic process 2-3:"

"i.e."

s3 = s2 "….for isentropic process 2-3"

"At zero magnetic field, we have entropy:"

s4 = R * ln(2*J + 1)

"Therefore, heat transfer to refrigerator, Qpercycle:"

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Qpercycle = m * T4 * (s4 – s3) "J / cycle"

"And, heat transfer rate, Q for 30 cycles/h:"

Q = Qpercycle * (30 / 3600) "W"

Results:

Unit Settings: SI K kPa kJ mass deg

B = 0.3821
H4 = 0 [A/m]
k = 1.380E-23 [J/K]
m = 0.025 [kg]
μ_B = 9.273E-24 [A-m^2]
N_0 = 6.023E+23
Qpercycle = 0.001342 [J/cycle]
s2 = 22.85 [kJ/kg-K]
s3 = 22.85 [kJ/kg-K]
T2 = 2.5 [K]
ξ_2 = 0.07692

H2 = 231,300 [A/m]
J = 1.5
Lande$_g$ = 1.97
μ_0 = 0.000001257 [J/A-m^2]
n = 2.409E+25 [per·kg]
Q = 0.00001118 [W]
R = 16.662 [J/kg-K]
s2byR = 1.372
s4 = 23.1 [kJ/kg-K]
T4 = 0.22 [K]

Thus:

Heat transfer rate from low temp. source = Q = 0.00001118 W …. Ans.

"**Prob.4.3.36** A magnetic refrigerator uses chromium methyl ammonium alum as the working salt. Heat addition per unit mass from low temp source at 0.08 K to the working salt is 1.258 J/kg. The magnetic field intensity at the end of isothermal heat addition process is 0 A/m. Determine the magnetic field intensity at the beginning of the isothermal heat addition process. [1]"

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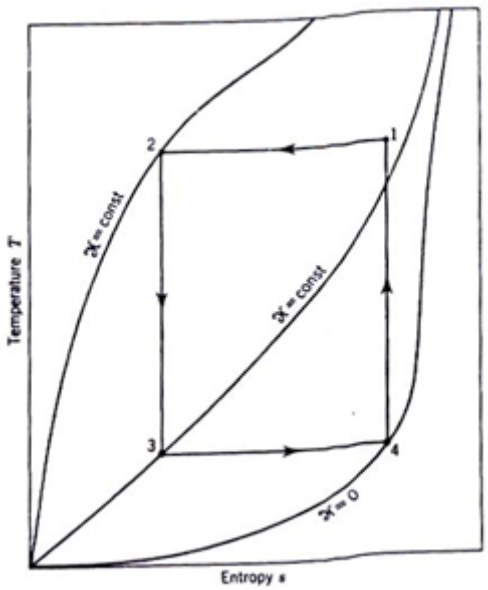

"Solution:"

"Props of Chromium methyl ammonium alum:"

"Use the EES Procedure written earlier:"

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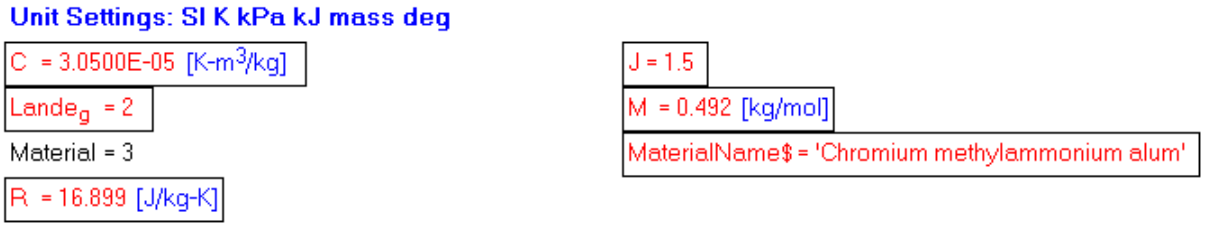
Material = 3

CALL Props_Paramag(Material: MaterialName$, Lande_g, J, M, R, C)

We get:


Unit Settings: SI K kPa kJ mass deg
C = 3.0500E-05 [K-m3/kg]
Lande_g = 2
Material = 3
R = 16.899 [J/kg-K]
J = 1.5
M = 0.492 [kg/mol]
MaterialName$ = 'Chromium methylammonium alum'

"Further:"

M = 0.492 [kg/mol]

N_0 = 6.023 * 10^23 "per mol …. Avogadro's No."

mu_B = 0.9273 * 10^(-23) "[A-m^2] … Bohr magneton"

mu_0 = 4 * pi * 10^(-7) "[J/A-m^2] …permeability of free space"

k = 1.3805 * 10^(-23) [J/K] "…Boltzmann constant"

n = N_0 / M "…no. of ions per unit mass"

T4 = 0.08[K]

H4 = 0 [A/m]

T3 = T4

Lande_g = 2

J = 3/2

R = 16.899 [J/kg-K]

Qpercycle = 1.258 [J/kg]

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"Now, at zero magn. field, we have for entropy, s4:"

s4 = R * ln(2*J + 1) "..J/kg-K.... finds s4"

"And, Qpercycle:"

Qpercycle = T4 * (s4 – s3) "J / kg .... finds s3"

"To find H3, the mahnetic field at point 3:"

Xi_3 = Lande_g * mu_B * mu_0 * H3 / (2 * k * T3) " ....finds H3"

"And, get s3byR using the EES Procedure for Brillouin Function:"

CALL Brillouin_Function_entropy(Xi_3, J: B, s3byR)

"And:"

s3 = R * s3byR "J/kg-K"

"=="

Results:

Unit Settings: SI K kPa kJ mass deg

B = 2.689	H3 = 94,730 [A/m]	H4 = 0 [A/m]
J = 1.5	k = 1.380E-23 [J/K]	$Lande_g$ = 2
M = 0.492 [kg/mol]	μ_0 = 0.000001257 [J/A-m^2]	μ_B = 9.273E-24 [A-m^2]
n = 1.224E+24 [per·kg]	N_0 = 6.023E+23	Qpercycle = 1.258 [J/kg]
R = 16.899 [J/kg-K]	s3 = 7.702 [kJ/kg-K]	s3byR = 0.4558
s4 = 23.43 [kJ/kg-K]	T3 = 0.08 [K]	T4 = 0.08 [K]
ξ_3 = 0.9995		

Thus:

Magnetic field intensity at the beginning of the isoth. heat addition process:

H3 = 94730 A/m ... Ans.

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Prob.4.3.37 Nuclear paramagnetic materials obey the Brillouin expression, with the exception that the Bohr magneton must be replaced by the nuclear magneton (μ_N) = 5.0506 × 10^{-27} A-m^2 and the nuclear quantum number I replaces the atomic constant, J. Determine the magnetic moment per unit mass and entropy for copper as a nuclear paramagnetic system with g = 2, I = 1/2, M = 63.54 g/mol, and R = 130.8 J/kg.K. The copper temp is 0.004 K and the applied magnetic field is 4.35 MA/m (= 5.47 T).[1]

"EES Solution:"

"We have:"

M = 0.06354 [kg/mol]"…for copper"

I = 1/2 "…Nuclear Quantum no. for copper"

N_0 = 6.023 * 10^23 " per mol …. Avogadro's No."

mu_N = 5.0506 * 10^(-27) "[A-m^2] .. Nuclear magneton"

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mu_0 = 4 * pi * 10^(-7) "[J/A-m^2] …permeability of free space"

H = 4.35 * 10^6 [A/m]

k = 1.3805 * 10^(-23) [J/K] "…Boltzmann constant"

n = N_0 / M "…no. of ions per unit mass"

Lande_g = 2 "…for copper"

R = 130.8 [J/kg-K] "…for copper"

T = 0.004 [K] "…by data"

"Calculations:"

"Then, we get:"

Xi = Lande_g * mu_N * mu_0 * H / (2 * k * T)

"And, get Brillouin Function, B and sbyR using the EES Procedure:"

CALL Brillouin_Function_entropy(Xi, I: B, sbyR)

"Magnetic moment for copper:"

I_cu = (1/2) * n * Lande_g * mu_N * B

"And, Entropy, s:"

s = R * sbyR "J/kg-K"

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Results:

Unit Settings: SI K kPa kJ mass deg

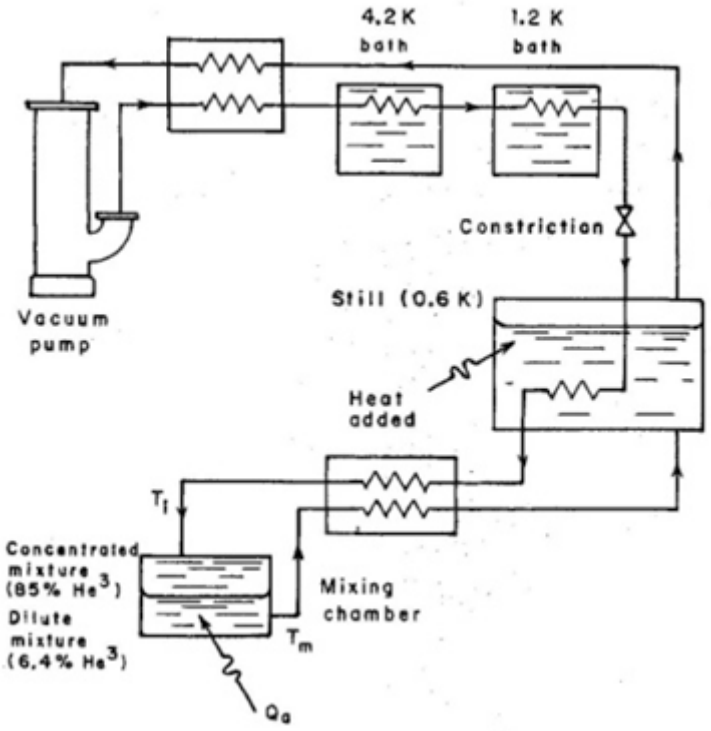
B = 0.4621	H = 4.350E+06 [A/m]
I = 0.5000	I_{cu} = 0.02212 [A-m^2/kg]
k = 1.380E-23 [J/K]	$Lande_g$ = 2
M = 0.06354 [kg/mol]	μ_0 = 0.000001257 [J/A-m^2]
μ_N = 5.051E-27 [A-m^2]	n = 9.479E+24 [per·kg]
N_0 = 6.023E+23	R = 130.800 [J/kg-K]
s = 76.15 [J/kg-K]	sbyR = 0.5822
T = 0.004 [K]	ξ = 0.5

Thus:

Magnetic moment per unit mass = I_cu = 0.02212 A-m^2/kg … Ans.

Entropy = s = 76.15 J/kg-K … Ans.

Prob.4.3.38 A He3-He4 dilution refrigerator operates with a flow rate of He^3 of 1.53 × 10^{-4} mol/s. The liquid He^3 enters the mixing chamber at 0.04 K and the dilute phase leaves the mixing chamber at 0.03 K. Determine the heat transfer rate to the mixing chamber from the low temp region.[1]



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EES Solution:

n_3 = 1.53 * 10^(-4) [mol/s]

T_i = 0.04 [K] "… temp of He3 mixture entering the mixing chamber"

T_m = 0.03 [K] "… temp of He3 mixture leaving the mixing chamber"

C_1 = 94 [J/mol-K^2]

C_2 = 12 [J/mol-K^2]

"Then, we have:"

h_m = C_1 * T_m^2 "J/mol"

h_i = C_2 * T_i^2 "J/mol"

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"Therefore, heat transfer rate to mixing chamber from low temp region:"

Q_a = n_3 * (h_m – h_i) "W"

Results:

Unit Settings: SI K kPa kJ mass deg

$C_1 = 94$ [J/mol-K^2]	$C_2 = 12$ [J/mol-K^2]	$h_i = 0.0192$ [J/mol]
$h_m = 0.0846$ [J/mol]	$n_3 = 0.000153$ [mol/s]	$Q_a = 0.00001001$ [W]
$T_i = 0.04$ [K]	$T_m = 0.03$ [K]	

Thus:

Heat transfer rate to mixing chamber from low temp region :

Q_a = 0.00001001 W = 10.01 μW … Ans.

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